THE INVESTIGATION OF STUDENT UNDERSTANDING OF ATOMIC STRUCTURE AND BONDING

A thesis

submitted in partial fulfilment

of the requirements for the Degree

of

Master of Science Education

in the

University of Canterbury

by

Loanne Metcalfe

University of Canterbury

1996

DEDICATION

I would like to dedicate this document to the memory of

Ballinda Myers

chemistry teacher and science adviser

whose friendship, encouragement and wisdom I deeply valued

and whose courage will always be an inspiration

CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

This purpose of this research project was to determine if there were misconceptions about atomic structure and bonding among Form 6 chemistry students. A questionnaire was given to 110 students from six classes in four Christchurch schools and uncovered several misconceptions. Students whose answers indicated specific areas of confusion were chosen to be interviewed. At least three students per class, twenty students in all, were interviewed within two weeks of the questionnaire and again at the end of the year. The interviews provided details of their misconceptions and in some cases revealed the cause. Teachers of the six classes used in the research were interviewed for their insight into the cause of the misconceptions and possible means of avoiding them. The discussion analyses the research techniques and compares the performances of the six classes. The possible causes of the misconceptions are discussed. The summary includes some suggestions for teaching strategies to help prevent these misconceptions from forming.

CHAPTER I

INTRODUCTION

Chemistry is defined in the new national curriculum as 'the study of the properties of matter and the changes it undergoes' (Chemistry in the New Zealand Curriculum, 1994). The feature that is basic to the understanding of chemistry is worded as follows in the third Achievement Aim of that curriculum - 'In their study of chemistry, students will use their developing scientific knowledge, skills and attitudes to understand important concepts in chemistry and major patterns of chemical behaviour.' It is this conceptual nature of chemistry - originating in the ancient Greek proposal of the atom as the ultimately small particle (Revised Nuffield Chemistry: Chemists in the World, 1979) - that established chemistry as a separate science. But it is this same conceptual nature of chemistry that poses the greatest problems of understanding for students of chemistry, as any reading in the field of chemical education will attest (Bodner,1992; Nakhleh,1992; Johnstone,1993; Fensham,1994)

As a science, chemistry owes much of its early development to alchemy, an activity which originated in North Africa and spread to Europe. Alchemists were not true scientists, but primarily magicians or mystics. By the 15th century their efforts were chiefly focused in two areas; - finding a cure for all diseases and discovering a way to turn 'base metals into gold'. As the scientific revolution spread, sparked by the works of Galileo and Newton, and later Lavoisier in chemistry, the practice of alchemy ceased, but left as its legacy knowledge of many chemical substances and a variety of methods of extraction (Christiansen and Garrett,1960). Chemistry was gradually introduced as a subject for university teaching, although until the middle of the 18th century it was regarded as an adjunct of medicine. From 1750 on chemistry became a teaching subject in its own right and Chairs in Chemistry were established in the universities as industrial pressure demanded a supply of analysts and research chemists (Johnstone,1993).

Present day chemistry is built on the foundation of the Atomic Hypothesis put forward over 180 years ago by John Dalton. He was able to show that measurements of the masses of the elements that combine together can be used to work out the relative masses of atoms and so provided a practical method for determining the formulae of compounds. His hypothesis developed into the Atomic Theory, which is the basic concept of chemistry. (Revised Nuffield Chemistry, 1975)

During the 19th century chemistry was introduced into high schools, but its introduction was considered to fill a vocational rather than an intellectual need, and it was not until the 20th century that it was recognised as a subject that could contribute to the 'training of the mind'. In an effort to be suitable for such mind training, the chemistry curriculum was mainly concerned with the 'preparation and properties of gases, a list of laws and definitions..., a few industrial processes with details of temperatures and pressures,...practical work consisting of 'observations of preparations and properties' and 'analytical exercises of varying complexity'- in other words a lot of rote learning and regurgitation interspersed with a few demonstrations (Johnstone,1993). Sadly, the situation did not really change for a great many years. Johnstone, a Scot who is highly regarded as a chemical educator, recalls finding a set of model notes in his high-school laboratory dated 1900 that were identical to those he was working from in 1960.

In 1947, James Conant started a movement away from the observational philosophy of science with the publication of his book 'On Understanding Science'. In it he argued that scientists invent and use conceptual schemes and that these are modified over time and may even be discarded. Others, including Thomas Kuhn, expanded the role that concepts play in human understanding. So science began to be regarded as a set of concepts that were constantly being modified and refined (Novak, 1984). By the early '50's questions began to be asked about the relevance of what was being taught in school science generally (Andersen, 1969) but although science curriculum revision was frequently discussed in both the U.K. and the U.S., little change occurred due to lack of funds. However, in 1957 with the launch of Sputnik and the subsequent cold-war race for space supremacy, there was an immediate demand for more scientists, and suddenly the funding was also available. In chemistry the Nuffield Chemistry programme was developed in the U.K. (Nuffield Chemistry,1966), and in the

U.S. there were several similar developments, the CBA, Chemical Bond Approach (Westmeyer,1969), and the CHEM Study programme (Campbell,1962) among others. In all these cases, there was a major change away from the rote learning of individual reactions and a move towards a conceptual approach, that is, one 'in which the fundamental, unifying concepts of chemistry are stressed' (Merrill,1969). At the same time, individual practical work was given a great boost with the 'discovery 'method (Ausubel,1969), where students were encouraged to plan their own experimental work and hopefully to derive or discover the truths of chemistry for themselves. A new chemistry curriculum for New Zealand was produced in 1967 and was influenced to a fair extent by the American CHEM Study programme; many schools adopting its text book 'Chemistry : An Experimental Science'(1960). The result was an increase in enrolments for chemistry at high schools and universities for a few years. Altogether a great deal of excellent work and a lot of money went into the development of the programmes throughout the 1960's and into the early '70's. Chemistry educators everywhere were confident that the new approach would 'awaken the spirit of investigation' and bring students 'to a reasonable standard of lively competence' (Revised Nuffield Chemistry,1975). It was only gradually that chemistry teachers and educators became aware that their own enthusiasm for the programmes were not being met by those of their students, and falling numbers in high school classes and university chemistry departments were noted (Garforth,1982; Johnstone,1993). This was also true for New Zealand. Clark and Vere-Jones (1987) found that in the eleven years from 1974 to 1986 there was a significant drop in the number of boys taking senior chemistry and only a slight rise in the number of girls. Harland (1991) reported that the Bursary entrance figures indicated that chemistry had the lowest growth rate over the preceding decade. As Johnstone puts it 'The sad fact was that we did not produce a generation of people thirsting for chemical knowledge'.

The next curriculum revolution was more gradual. As the field of education opened up during the 20th century philosophers and psychologists had begun to question the process of learning; - what was being taught and whether it was being learnt. Piaget asserted that the 'child did not acquire knowledge merely by being told or by reading it', rather that 'the child must act on the knowledge' (Mallison,1975) And science received its share of attention. In New Zealand Karl Popper, writing during his tenure at Canterbury University College

(1937-1944) had written that science education demanded 'an active inquiry by students posing problems and looking for answers'. He went on 'Our present system is based on the passive view of science -'The Bucket Theory' of the mind', that is, the mind is an open vessel and the teacher is meant to pour the knowledge in. Ausubel (1969) questioned the limitations of learning by discovery. He stated that the most schools could hope to achieve by this method was to 'improve the critical - thinking and problem-solving abilities of the majority of their students', and that striving to make every child a creative thinker was impossible'. Gagne (1969) was concerned that 'the curriculum was not simply and solely something to be learned', suggesting that the content of a curriculum could affect its learning. In the late 70's and early 80's there were projects in several countries that investigated children's learning. The Project to Enhance Effective Learning (PEEL) Project at Monash University in Melbourne with White and Gunstone was an extensive study set out to 'develop methods of probing students' understanding and to see how alternative conceptions of phenomena' held by students could be brought 'into accord with scientists' conceptions' (White, 1988). The work of the Children's Learning in Science Project at Leeds University in the U.K. directed by Rosalind Driver and the work of the Learning In Science Project at Waikato University headed by Osborne and Freyburg 'used extensive individual student interviews, surveys and observations to find out the students' views of the various phenomena in science' (Schollum, 1992). All of these studies clearly demonstrated that 'the learning of science by children ..is an investigative constructive process'. Research in this field 'seeks, in various contexts, to define conditions that promote optimal students inquiry', and the teaching 'that can provide those conditions. The general philosophy that supports this view has come to be called constructivism'. (Hawkins, 1994). Laverty and McGarvey (1991), working with the Children's Learning in Science Project (CLIS) at Leeds University describe this approach as one where the students are perceived as active learners who come to science lessons already with ideas about natural phenomenon, which they use to make sense of their everyday experiences. They have also developed a constructivist teaching sequence that allows pupils not only to adopt new ideas but also to modify or replace existing ones. This is the challenge to the teacher in this philosophy; - to help students to 'make better sense of their world', leading to better understanding of the concepts of the scientist' (Carr, 1990). Research into teaching strategies that can achieve this continue in New Zealand, the U.K., and Australia. The new Science curriculum in New Zealand (1993) and the senior science curricula in Biology, Chemistry and Physics that followed in 1994 have been much influenced by the principles of this educational view, to the extent that the old terms of Biology, Chemistry and Physics have been replaced in the Science in the New Zealand Curriculum (1993) by the terms 'Making Sense of the Living World', 'Making Sense of the Material World', and 'Making Sense of the Physical World'. It is important to note, however, as has recently been pointed out in several strong defences of the philosophical base of the documents - 'making sense' does not mean that all learners construct their own meanings, and that all such constructs would have equal validity' (Butler and Longbottom, 1995). As Haigh (1995) points out, 'the curriculum writers used the phrase to mean the development of an understanding of scientific knowledge' and this may sometimes mean that students will need to change their firmly held 'common sense' views about the world (Carr, 1995).

All of the developments outlined above had a major impact on the preparation of the new Chemistry in the New Zealand Curriculum statement

* chemistry as an academic subject
* curriculum changes of the 1960's
* research into children's learning
* constructivist teaching strategies

The academic nature of the subject and the conceptual approach of the '60s is retained in the list of the central concepts of chemistry and the major patterns of chemical behaviour included in the third Achievement Aim. The research into children's learning in science (the Learning in Science Projects (LISP) that started at Waikato University in 1979 is based in a constructivist approach to science teaching and has had a strong influence on Science in the New Zealand Curriculum and the three senior science documents which developed from it. It is fair to mention that there were at least two other significant developments that also impacted on the chemistry document; - the science-technology-society debate and the delivery of content within a context as opposed to the delivery of content first followed by an appropriate contextual development. However these issues are not considered to have a major bearing on the focus of this research.

The writer was one of three writers of this new curriculum. During the preparation of the list of chemical concepts for the third Achievement Aim, her attention was directed to the problems students have with the conceptual nature of the subject. The concepts listed in the new curriculum are:

* the atom is the basic unit of chemical composition and chemical change
* the chemical behaviour of the atom of an element is largely determined by the electron configuration of its atoms
* all the important forces between atoms, molecules and ions are electrical
* at any temperature greater than absolute zero the particles in any sample of matter are in constant motion
* chemical changes and changes of state have energy changes associated with them
* the reversibility of chemical reactions and the nature of equilibrium systems

It will be noted that the first three concepts are concerned with atomic structure and bonding. This is in accordance with the traditional view that 'Atomic Theory' is central to the understanding of chemistry. As Cannizzaro in 1861 stated 'I have come to the conclusion that...it is impossible to eliminate atomic theory ..in the course of my teaching'. The behaviour of matter is explained in terms of the behaviour of its atoms, and 'without a grasp of them it is not possible to learn the subject' (Revised Nuffield Chemistry, 1975). Fensham (1994) outlined three approaches to the introduction of chemistry and one of them, the 'Atomic structure approach' still reflects the conceptual approach that distinguished chemistry teaching in the '60s and '70s. As argued by Satchell (1982) it proposes that the student should be introduced to chemistry with a description of atoms and their structures and then proceed into related concepts and reactions. A second approach is to start with chemical reactions and use them to introduce the underlying atomic structure and bonding concepts, such as was done with the Nuffield programmes. A third approach is to introduce chemistry through the study of substances and leave atomic theory until the end of the course. No matter what way it is approached, atomic theory and the bonding of atoms, molecules and ions, - the 'corpuscular' nature of matter (de Vos and others, 1987) - is central to the study of chemistry.

There have been a great many studies of the problems students have with learning these concepts, the language that is used to describe them and the links that need to be established between the concepts and the reactions studied in the laboratory. de Vos and others (1987) report on the dominant role played by atoms and molecules in the language of chemistry and point out that 'Familiarity with the world of atoms and molecules that is so indispensable to the professional chemist, becomes an enormous obstacle as soon as the chemist tries to communicate the subject with a layman...or an elementary chemistry student'. Johnstone (1993) speaks of a triangle that has three major components; 'the macrochemistry of the tangible, edible, visible; the submicrochemistry of the molecular, atomic and kinetic and the representational chemistry of symbols, equations, stoichiometry and mathematics'. He suggests that professional chemists work well within the triangle (Figure 1) and 'slide from one corner to another as our thinking requires' but 'few of our students follow us there with any great ease'.

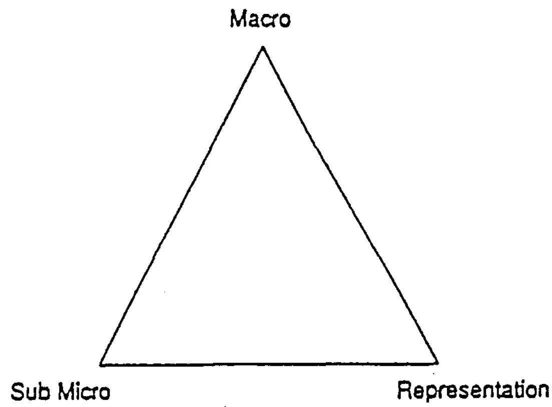


Figure 1. The three basic components of chemistry: macrochemistry, submicrochemistry and representational chemistry.

Johnstone points out that 'much of the old chemistry was concerned only with the macro and representational corners and shared edge' of the triangle; the submicro part was often missing. He argues that the subject' has many problems arising out of its conceptual structure' that may be at variance with how people learn. Moreover teachers at times may mix the macrochemistry with the submicrochemistry terms. Selley (1978) for example writes of the 'category mistake' of confusing substances with their molecular particles. Such sentences as

Hydrogen ions are reduced to hydrogen gas.

When lead bromide is electrolysed, lead ions are converted to lead metal.

mix the macroscopic terms of gas, metal and compound (lead bromide) with the submicroscopic term 'ions'. Several authors write of the results of such confusion. Gabel (1987) reports that students after an experiment with wax concluded that the molecules of a soft substance must themselves be soft. Ben-Zvi (1988) points out that since students cannot avoid the word atom from their very first chemistry lesson, their view of a copper atom for example, is likely to be a small lump of copper, while a mercury atom will mean a small drop of mercury. This misconception that the properties of the substance must be reflected in the properties of the atom or molecule leads to the conclusion that every chlorine molecule must be green !

There have been many specific studies of the misconceptions that students have in this area of atomic structure. Apparently the structure of the atom is generally accepted. Cros (1986) for example found that 95% of a large sample of university students did know about the atom and its fundamental particles, although there were some misconceptions about the interactions of the particles. But more major misconceptions appear when other terms are introduced, molecules, elements and compounds. Griffiths and Preston (1989) interviewed Canadian high schools students and identified 52 misconceptions about atoms and molecules, some of which they argued could have arisen as the results of instruction. Mitchell and Gunstone (1984) investigated students' views of the relationship between atoms and elements, and molecules and compounds after they had been introduced to their chemistry course through the 'substances approach' mentioned earlier. Here the introduction seeks to associate elements with atoms as their smallest particles on one hand and compounds with molecules on the other in an attempt to simplify the material. However as these descriptions are soon overturned when the students proceed with chemistry, they found this approach created much confusion.

Students also have similar difficulties with comprehending chemical bonding. Peterson and others (1986) investigated a number of misconceptions about covalent bonding and structure. Among them was confusion about the influence of electronegativity on the unequal sharing and position of the electron pair in many covalent bonds. They also found there was a strong tendency to identify intermolecular forces with the covalent bond within the molecule and a lack of awareness of the 'general difference in magnitude that exists between the strength of a covalent bond and the strength of an intermolecular force'. Treagust (1986) found a related misconception that 'covalent bonds are broken when a substance changes state'. Taber (1994) uncovered what he terms 'molecular framework' theories of ionic bonding. In spite of the fact that students knew that the lattice below represented sodium chloride, one set of students believed that because the sodium atom could only donate one electron, it could only form an ionic bond to one chlorine atom, whereas a magnesium atom (which loses two electrons to form an ion with a 2+ charge) could therefore form ionic bonds to two chlorine atoms.

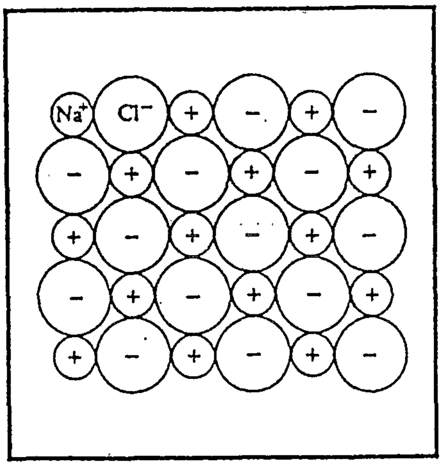


Figure 2: A layer of ions in a sodium chloride lattice

A second group had an historical view, suggesting that bonds are only formed between the atoms that donate/accept electrons, so that in sodium chloride (NaCl) a chloride ion (Cl^-) is bonded to the specific sodium ion (Na^+) that 'gave' it an electron. The third group considered that this stronger attraction remains intact even when the sodium and chloride ions are within the lattice, so that a chloride ion is bonded to just one sodium ion, but attracted to the other five sodium ions that surround it by 'just forces'. He goes on to suggest that these conjectures could arise from the standard presentation of ionic bonding and proposes that electrostatics be stressed when teaching bonding. His suggestion is backed by Ben-Zvi and others (1987) who point out that a description of the full model for the formation of an ionic crystal such as sodium chloride is cumbersome, and so teachers tend to present only that part that seems relevant,- that is, the electron transfer from the sodium to the chlorine. This may too easily lead the student to think that one atom of sodium reacts with one atom of chlorine to form an NaCl pair.

Studies of misconceptions of the metallic bond do not appear to have been so numerous, possibly because most texts describe a situation similar to the one in Form 6 Chemistry Revision (Sayes, 1986) that 'metals consist of many positively charged ions in fixed positions in a lattice. Moving between these ions are a 'sea' of delocalised electrons'. It is a common description; the International General Certificate of Secondary Education Chemistry Syllabus 1989 from the

University of Cambridge Local Examination Syndicate describes metallic bonding as 'a lattice of positive ions in a sea of electrons', and a well-known Australian text, CHEMISTRY ONE, (Elvins,1990) uses the same model. This oversimplifies a very complex situation in which the few valence electrons of one atom are loosely held and can move without a significant energy change into the empty orbitals of nearby atoms (Croucher and Packer,1975). However the model does help to account for the metal properties of conductance of heat and electricity, as well as malleability and ductility.

Much research in this area has been carried out on problems of language. As Ben-Zvi (1988) points out the shorthand used by chemists is a very good and efficient way of communicating. However the new student 'is not familiar with the ideas of atomic structure and bonding and the differences between atoms and molecules are not very clear'. For example, He stands for Helium the atom or the gas, or even the monoatomic molecule (Metcalfe and others,1970), but O is the atom of oxygen, while the gas is O_2 ! Dr Mary Budd Rowe (1983) found that students in their first year of a college chemistry course in the US were expected to assimilate 6000 units of information, - more new language than is usually found in the first year of a foreign language study. Bent (1984) pointed out that 'chemistry (and its models) is nothing if not a language...Chemistry is a foreign language twice over, - strange terms for strange things'. Both Johnstone (1993) and Ben-Zvi (1988) refer to Ausubel's internal factors, the set of concepts already held by the student that must be 'unpacked' and then 'repacked' in order to accommodate all this new information. If the students have a set of misconceptions to build on, it is possible they will distort their new information so that it will fit with their framework. And only so much conceptual information can be absorbed at the same time. So the language and the concepts combine to present the students with what may well be an overpowering challenge. As Byrne (1994) quotes one student;

> 'This is how I remember chemistry lessons - glimmers of meaning coming and going amidst a rising tide of panic in case I was asked a question. The teacher was nice enough: it was just that he spoke a different language.'

Do some of our first-year Christchurch chemistry students have problems similar to those reported ? It was the aim of this research to investigate what misconceptions, if any, our Form 6 chemistry students held in the area of atomic structure and bonding. Form 6 students were surveyed as this is the year when most New Zealand students commence their specialised study of chemistry. The research took the form of a questionnaire followed by interviews with selected students, followed by interviews with the teachers of the classes concerned.

The questions posed for this research were:

* What are some of the misconceptions that Form 6 chemistry students have with the basic concepts of atomic structure and bonding ?
* Why have these misconceptions arisen ?
* How might teachers introduce and develop this topic with their students so as to prevent misconceptions from forming ?

CHAPTER II

RESEARCH METHOD AND RESULTS

1. RESEARCH RATIONALE

The research was divided into three parts. A questionnaire was administered to 110 students for the first part of the research to screen for misconceptions. Twenty students whose responses indicated confusion were then interviewed in order to determine if this confusion could be related to specific misconceptions. As the students of six different teachers answered the questionnaire, the third part of the research was to interview each teacher to determine if there was a relationship between the performance of their students and the way that they presented the material to their class.

2. METHOD OF SURVEY: THE QUESTIONNAIRE

(1) How The Questionnaire Was Designed

The questionnaire was drawn up using the content from the Atomic Structure and Bonding area of the new curriculum - which is, in fact, identical with the previous one. It was broken down into eight sections; Atoms, Ions, The Shape and Size of Molecules, Metallic Bonding, Molecular Bonding, Covalent Networks, Ionic Bonding and Bonding in General. The questionnaire is included as Appendix A.

The primary purpose of the questionnaire was to investigate student understanding. Therefore a major goal in its design was to present enough information so that lack of fact recall did not prevent the students from answering the questions.

The actual format of each section of the questionnaire with the information supplied to the students is presented in the results tables. The rationale behind the inclusion of each section will be dealt with before the results tables are presented.

(a) **<u>Section A: Atoms</u>** This section dealt with the three major sub-atomic particles, protons, neutrons and electrons, and was designed to uncover misconceptions students could have about the role of protons in identifying the atom; the relationship or lack of it between the numbers of protons, neutrons and electrons; and the identity of the sub-atomic particles that take part in chemical reactions.

(b) **<u>Section B: Ions</u>** This section was designed to investigate the students' understanding of the changes that occur in atoms when they form ions. The last question of this section was prepared to determine whether students did confuse the 'levels' in terminology. This was included to test the view of Johnstone (1993) that students cannot move easily between the macroscopic forms, element and compound, and the submicroscopic terms, atoms, ions and molecules.

(c) **<u>Section C: Shape And Size Of Molecules</u>** The questions in this section deal with a part of the syllabus that is introduced for the first time at Form 6. It was included to test for misconceptions between the bonding present in the molecule and its resultant shape. The last question was included to find out what proportion of students were aware of the incredibly small size of a molecule.

(d) **<u>Section D: Metallic Bonding</u>** This short section was included mainly to ensure that all four of the common crystalline solids in the syllabus were covered in the questionnaire. The two questions here relate directly to the nature of the metallic bond.

(e) **<u>Section E: Molecular Bonding</u>** This is another section on material introduced for the first time at Form 6. The questions were about the type and strength of bonds found in molecular crystals and were designed to uncover any confusion between intermolecular and intramolecular bonding.

(f) **<u>Section F: Covalent Networks</u>** The questions on the type of particle and the bonding between particles were used to determine students' awareness of the nature of the bonding in these giant covalent network crystals.

(g) **<u>Section G: Ionic Bonding</u>** Ionic crystals are the last of the four crystalline solids and the questions used here were meant to discover any misconceptions about the nature of the particles in an ionic crystal and their bonding.

(h) <u>Section H: Bonding In General</u> This section consisted of four statements, two on the nature of bonding, and two on the types of particles present in a compound. Students were asked to agree or disagree with the statements and then give a justification for their answer. The statements were included to reveal understanding and were designed to serve as a basis for interview.

(2) How The Questionnaire Was Administered

The questionnaire was administered to six Form 6 chemistry classes at four schools in the Christchurch area. This gave a total of 110 students which was considered large enough to give some indication of common misconceptions that might exist with this material. In order to include equal numbers of female and male students from the sample, two single-sex schools, one female and one male, and two co-ed schools were chosen. The schools selected were close to the school of the writer so that student interviews could be arranged during lunch hours and free periods. To avoid identification the schools will be referred to as schools W to Z and in the case of the two schools W and X where two classes were used, the classes will be referred to as W1 and W2, and X1 and X2. In these two schools, each class was taught by a different teacher, although the material was covered at the same time with the teachers working in close consultation as to the depth of treatment. In all cases, the questionnaire was administered at least ten days after the Atomic Structure and Bonding section of the curriculum had been completed by the class, and it was emphasised that the results would not be counted towards the students' Sixth Form Certificate marks.

The questionnaire was administered by the class teacher under test conditions, as it was not possible for the writer to leave her own classes for this purpose. Also, as the questionnaire did not 'count' for Sixth Form Certificate, it was felt that the class teacher would have more success with gaining the cooperation of the students. Before starting the questionnaire, the outline of the research was explained to the class concerned by the teacher, and students were given the opportunity to opt out of the paper. It was explained at the top of the questionnaire that the results would be analysed and from them some students would be approached for two interviews, one the following week and one after

their exams at the end of the year. As the approach for the interviews was made through the class teacher, the students had the opportunity not to be interviewed if they wished. At the time of the first interview students were asked to complete a form giving permission for the results to be used in this research.
Twenty minutes was allotted to the students to complete the questionnaire. 110 papers were handed in and scored. In all questions, a blank was recorded as incorrect.

(3) How The Questionnaire Was Analysed

Each question of sections A to G with the exception of the last part of section B, was marked for correctness. In a few cases where the 'correct' answer is a matter of debate, the more usually accepted answer has been deemed correct. These cases will be dealt with in the analysis of the questionnaire results.
In the last part of section B, and in section H, the questions were designed to serve as a basis for discussion.

3. RESULTS OF THE QUESTIONNAIRE

In presenting the results of the questionnaire, the findings of each section will be reported in a table. For most sections, these results will also be presented on a bar graph. Each section will conclude with a discussion of the results. Any factor that might have influenced the answers given by the students will be noted.

A second table will be presented for each section showing the percentage of correct answers per class for each question. This was done to see if such factors as teaching presentation and programme timing affected class performance. It is realised that the results of this comparison can only be used in a fairly general way. With such a relatively small number of students in each class, a difference of one student can look much more significant when translated into percent. The significance of these tables will be considered in the discussion.

(a) Section A: Atoms In this section on Atoms the students had a choice of three answers; 'True in all cases', 'True in some cases' and 'Never True'. The overall percent of students recording each choice is shown below in boxes below opposite the question concerned in Table 1. In each case, the correct answer is bold and in italics. Figure 3 presents this information in a bargraph.

TABLE 1

Percentage of students responding to each choice of the questions about Atoms

Statements	True in all cases	True in some cases	Never true
	Percentage of all students N = 110		
1. The protons of an atom are found in the nucleus	*91*	2	7
2. The number of neutrons of an atom equals the number of protons	25	*70*	5
3. The number of protons determines the identity of the atom	*64*	20	16
4. The number of protons in the nucleus of an atom equals the number of electrons outside the nucleus	*52*	34	14
5. Only the electrons take part in chemical reactions	*71*	17	12

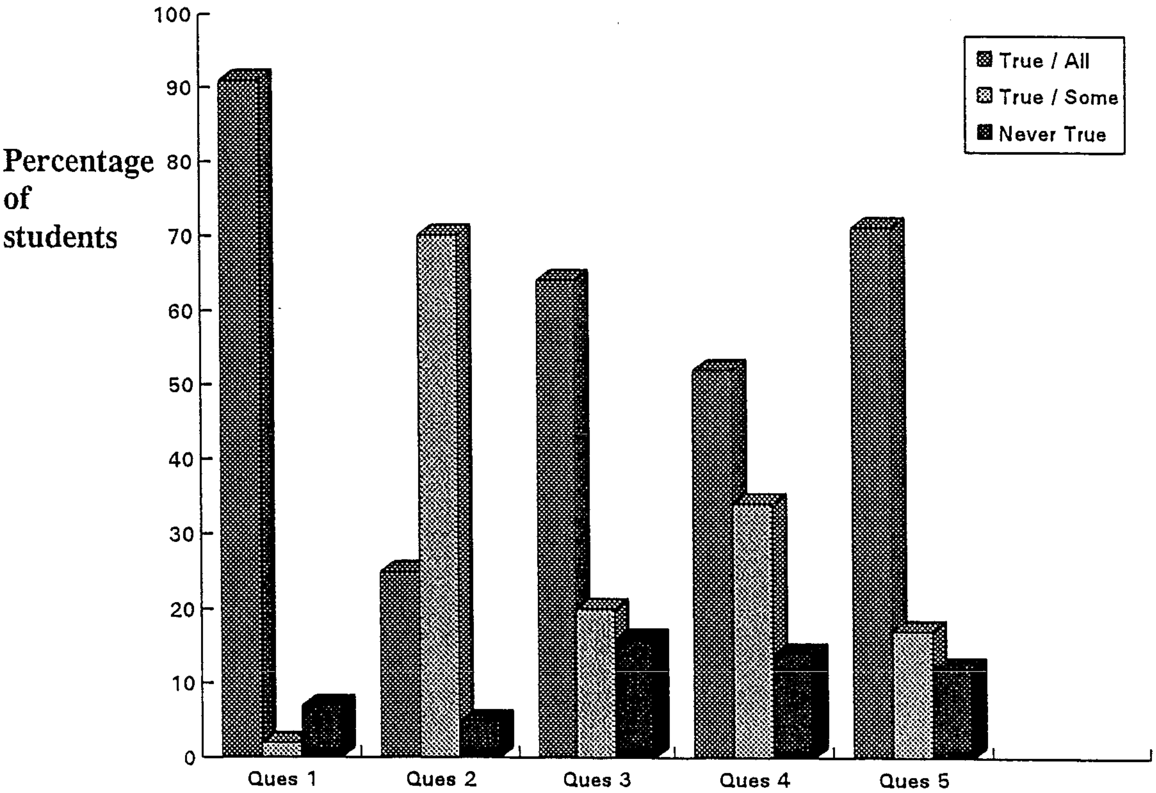


FIGURE 3: The percentage of students responding to each choice of the questions about Atoms

91% of the students recognised that protons are found in the nucleus; it would appear that 7% may have confused them with electrons. The scores for questions 2, 3 and 4 indicate that more students are uncertain of these facts. The fourth question could have been misunderstood if the students failed to read the phrase 'of an atom' and therefore considered ions in their answer. In question 5 nearly 30% of the students consider that protons and neutrons can take part in chemical reactions.

Table 2 shows the percentage of correct answers from each class in the survey.

TABLE 2

Percentage correct responses by classes for Table 1

Ques	Class W1	Class W2	Class X1	Class X2	Class Y	Class Z
A1.	95	80	100	83	94	94
A2.	57	57	80	72	88	88
A3.	43	57	80	66	94	44
A4.	52	57	60	61	33	44
A5.	71	65	73	77	77	55
n	***21***	***20***	***15***	***18***	***18***	***18***

The differences for questions 1 and 5 are not really significant, but the other questions, especially questions 3 and 4 show a fair bit of variation. Class Y has very good results except for question 4; it may be that more of them missed the word atoms and were thinking of ions, whereas most of classes W1 and W2 appear unaware that the number of protons determines the identity of an atom.

(b) <u>Section B: Ions</u> The first four questions of this section on Ions were scored as in section A. The results are presented in Table 3.

TABLE 3

Percentage of students responding to each choice of the questions about Ions

Statements	Percentage of all students N = 110 True in all cases	True in some cases	Never true
1. When an ion forms from an atom the number of protons may change	5	16	*79*
2. When an ion forms from an atom the number of electrons may change	*76*	20	4
3. Only the outermost energy level (shell) is affected by gain or loss of electrons in a chemical reaction	*82*	14	4
4. In some reactions atoms of an element will form negative ions but in other reactions the same atoms will form positive ions	20	49(39)	*31*(42)

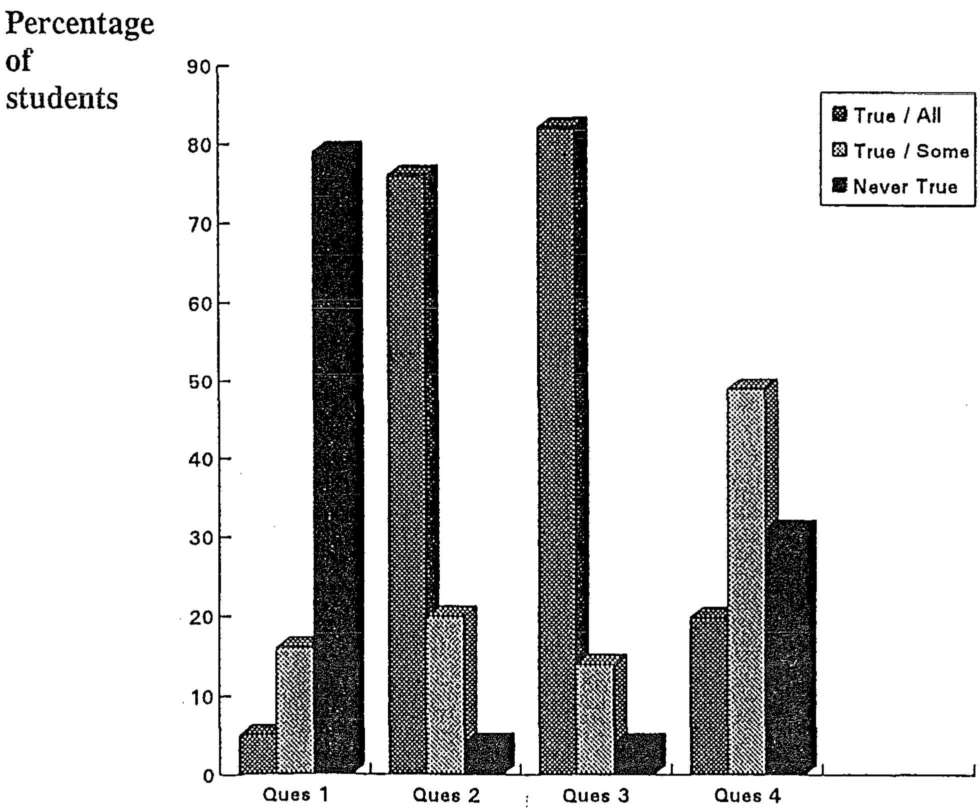


FIGURE 4: The percentage of students responding to each choice of questions 1 - 4 about Ions

Approximately eighty percent of the students across all classes got the first three questions of the section on Ions correct. For question 4, the correct answer is actually 'True in some cases'. However it was considered that the material needed for this conclusion would not have been covered in Form 6 chemistry at the time of the questionnaire and the accepted answer was therefore 'Never true'.

There are three points to consider here, and each could have contributed to the students' misconceptions.

* The first point is the one that is most likely to be responsible for the confusion of the students. Most elements only form one type of ion, metals forming positive ions and non-metals forming negative ions. The only two exceptions known to students at this level are both metals, iron forming the Fe^{2+} and Fe^{3+} ions and copper forming the Cu^{+} and Cu^{2+} ions, and both are positive. However all of these classes had started the oxidation section by the time of this questionnaire and had therefore been introduced to oxidation numbers. The oxidation numbers of the elements which indicate their oxidation state in compounds or radicals vary significantly, especially for the non-metals. Sulfur for example forms 2^- sulfide ion, whereas its oxidation state in H_2SO_4 is +6, while its oxidation state in SO_2 is +4. Oxidation numbers could easily become confused with ionic charges.
* The second point is that Hydrogen normally forms the H^+ ion, but in rare cases, such as the formation of lithium hydride, LiH, can form an H^- ion. This is not usually covered in Form 6.
* The third factor is that atoms that normally form negative ions can have their electrons stripped away consecutively to determine Ionisation Energies and therefore form positive ions. Although this does not occur in a chemical reaction (as the question asked) it could confuse students to whom it had been introduced. It is not normally covered in Form 6.

It was later found that both the second and third points had been covered in school X. Their answers to this question were therefore remarked with the answer 'True in some cases' being accepted as correct. The figures in brackets on the table indicate the percentage responses of the students from those two classes. It can be seen that 39% from the two classes did correctly mark 'True in some cases'. However it was not possible to determine the reasoning behind their choice except for the interviewed students. In the interview, four of the students had confused chemical reactions with ionisation energies, but the other two had correctly considered the usual positive hydrogen ion and the hydride ion in their reply. The five interviewed students in the other classes who had made the same error were simply unaware that atoms generally formed only one kind of ion and did not in fact confuse the issue with oxidation numbers.

Table 4 shows the percentage of correct results for these four questions about Ions from each of the six classes.

TABLE 4: <u>Percentage correct responses by classes questions 1-4 about Ions</u>

Ques Class	Class W1	Class W2	Class X1	Class X2	Class Y	Class Z
B1.	67	65	87	94	83	88
B2.	67	55	93	94	77	77
B3.	76	90	80	83	83	77
B4.	19	40	27	44	22	28
n	***21***	***20***	***15***	***18***	***18***	***18***

'True in some cases' was marked in question B4 as correct for classes X1 and X2. As already explained, 'Never true' was used for the other classes as that would be expected knowledge of students at this level. It can be seen that the majority of students, regardless of background, had problems with this question. Although none of the interviewed students had confused the question with oxidation numbers, this is still the most likely source of the misconception. Apart from that question, classes X1 and X2 appear to have the best understanding of ion formation.

In question 5 of this section, 56% of the total cohort were able to draw a correct diagram of the oxide ion alongside a similar diagram of an oxygen atom. The given diagram of the oxygen atom and the expected diagram of the oxide ion are presented in Figure 5.

FIGURE 5: The drawing of the oxygen atom presented on the questionnaire with the drawing that was expected from the students on the right.

The three questions below this diagram were related directly to it. The analysis of these results is given in Table 5.

TABLE 5

Percentage of students correctly responding to the questions about the oxygen atom and the formation of the oxide ion

Questions	Percentage of all students N = 110
a) How many protons does the oxygen atom have ?	80
b) How many protons does the oxide ion have ?	61
c) What is the charge on the ion ?	69

The results for each class for these three questions is shown in Table 6.

TABLE 6

Percentage correct responses by classes for the questions about the oxygen atom and the formation of the oxide ion

Ques	Class W1	Class W2	Class X1	Class X2	Class Y	Class Z
B.5(a)	86	75	73	94	83	66
B.5(b)	43	40	80	77	83	50
B.5(c)	52	50	80	94	77	66
n	*21*	*20*	*15*	*18*	*18*	*18*

Between thirty and forty percent of the students appear to have a considerable problem with the formation of ions from atoms. From a study of Table 6, it is apparent that these poor percentages are due largely to the performance of three classes; classes X1, X2 and Y having a notably better understanding than the others. The type of diagram requested for the ion is fairly common; also there was the additional assistance given by the diagram of the oxygen atom on the paper. Nearly half of classes W1 and W2 were unable to recall, even with assistance from the diagram, that one of the most common ions in their syllabus had a 2^- charge.

Question 6 was designed as a basis for discussion in the interviews. The students were asked to use the five terms, atoms, ions, molecules, elements and compounds to complete the following statements

a) _______ gain or lose electrons to form _______

b) _______ can combine chemically to form _______

and _______ can combine chemically to form _______

c) _______ are the simplest units of all _______

d) _______ are the simplest units of some _______

e) A compound cannot be made up of both _______ and _______

The purpose of the section was to lead into a discussion of the relationship between the terms in the interviews. However, an analysis of the answers given in the questionnaires indicated that 13% of the students had a problem with mixing the 'levels' of the terms. The terms atoms and elements were being used interchangeably, as in

***Elements* gain or lose electrons to form ions**, rather than atoms

***Elements* can combine chemically to form molecules**, rather than atoms

***Elements* are the simplest units of all molecules**, rather than atoms

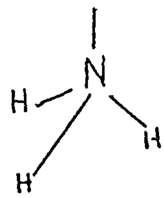
***Atoms* combine chemically to form compounds**, rather than elements

'A compound cannot be made up of both *elements* and ions', when they meant atoms and ions (the expected answer was molecules and ions) This indicates the problem with separating the macroscopic terms of element and compound from the sub-microscopic terms of atom, ion and molecule. This finding will be discussed with reference to the work of Johnstone (1993).

(c) **<u>Section C: Shape And Size Of Molecules</u>** This section on the shape and size of molecules was another area intended for interview discussion. The first two questions of this section and the sixth were multiple choice. The section was included to test understanding about the bonding and shape of ammonia, NH_3, a polar molecule commonly referred to in teaching this section. The sixth question had five options; the answers are indicative of the difficulty students have comprehending the very small size of particles, as has been reported elsewhere (Ben-Zvi and others,1988; Griffiths and Preston,1989). The questions and the percentage responses for each item are shown in Table 7.

TABLE 7

<u>Percentage of students responding to each choice of questions 1, 2 and 6 about Molecules</u>

Questions	Percentage of all students N = 110 a	b	c	d	e
1. Identify from the choices the reason for the trigonal pyramidal shape of the ammonia molecule.					
a) the unshared electron pair	18				
b) the shared electron pairs between the N and each H		21			
c) both (a) and (b)			*61*		
2. What is the type of bond between the N and each H ?					
a) polar covalent	*74*				
b) ionic		13			
c) non-polar covalent			7		
d) Van der Waals				6	
6. Approximately how many molecules are there in an average drop of water ?					
a) Less than 200	3				
b) Between 200 and 1000		8			
c) Between 10^{6} and 10^{12}			31		
d) Between 10^{12} and 10^{20}				25	
e) More than 10^{20}					*33*

Of the other questions, question 3 asked the students to identify the positive end of the polar ammonia molecule, and 62% were able to do so correctly. Question 4 asked if the students recognised that the behaviour of all the electrons, no matter which atom they came from was the same, and 71% replied correctly. The fifth question asked whether all the electron paris are the same distance from the central Nitrogen atom, and required a simple yes or no answer, but only 54% answered correctly. The question then asked the students to explain their answer; less than half responded and of those who did only 19% were able to give a correct explanation.

Figure 6 is a graphical representation of the correct replies to questions 1 to 4 about the shape and bonding of ammonia, and question six about the size of a water molecule.

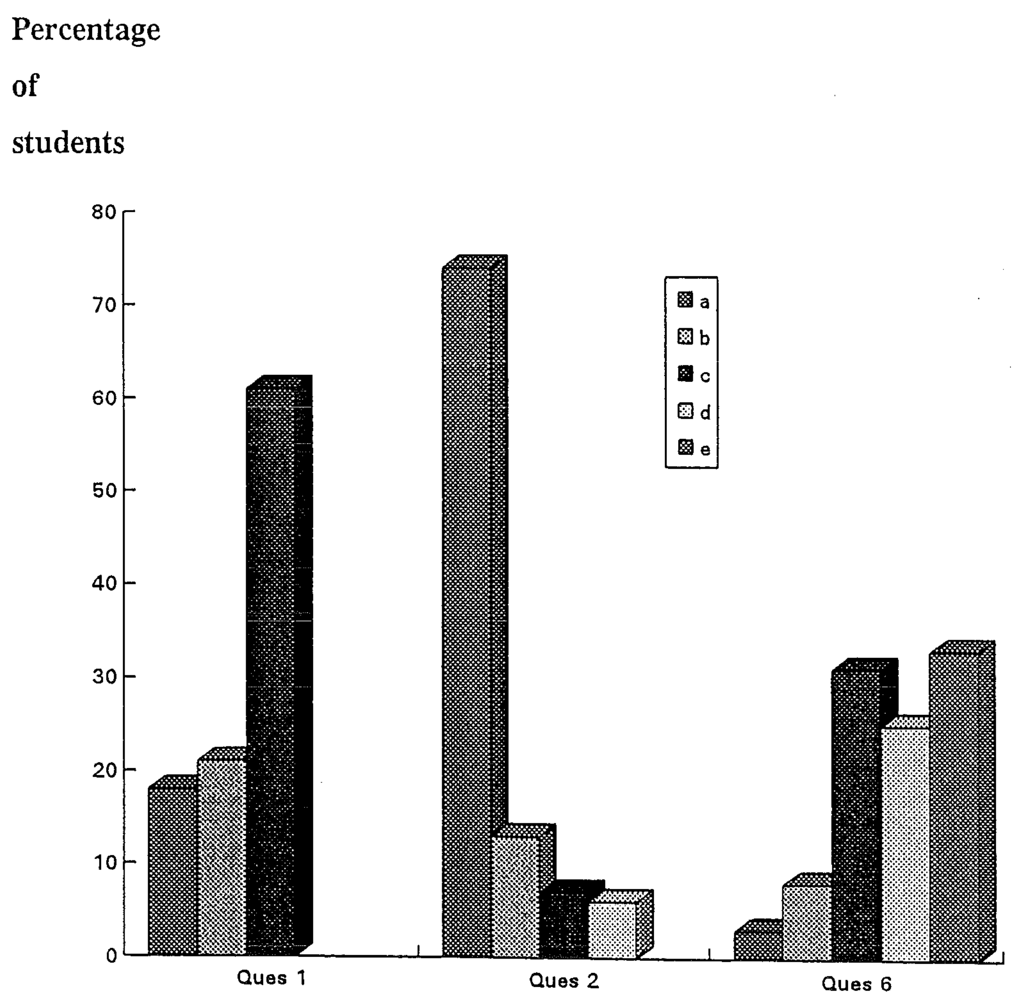


FIGURE 6 : The percentage of students responding to each choice of the questions about Molecules

The results of each class for these questions is shown in Table 8.

TABLE 8

Percentage correct responses by classes for the questions about Molecules

Ques	Class W1	Class W2	Class X1	Class X2	Class Y	Class Z
C1.	29	57	73	88	61	72
C2.	52	55	73	83	94	88
C3.	-	-	60	77	55	55
C4.	57	57	100	61	72	83
C6.	57	20	40	39	16	22
n	***21***	***20***	***15***	***18***	***18***	***18***

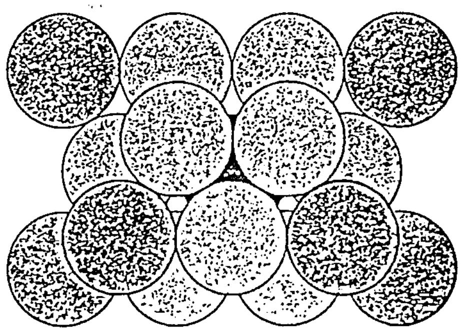
There are gaps in the table for Classes W1 and W2 as the reproduction of the questionnaires inadvertently cut off question C3 at the bottom of the page. Again in this table, two classes appear weaker than the others, although these are some anomalies. In question 4, class X2 is noticeably weaker than class X1.

This section on shape and size of molecules was relatively well done, considering this material is introduced for the first time in Form 6 and is not easy to assimilate. Of the first five questions only the one on the reasons for the shape and the question on the distance of the bonds from the central atom stumped more than 30% of the students overall - a result quite similar to that obtained with the much simpler material on atoms and ions. While only 33% of the students realised that there were more than 10^{20} molecules, at least more than half had the idea that it was a very large number.

(d) Section D: Metallic Bonding There were only two questions in this section on metallic bonding, both multi-choice. The overall percentages for each response are given in Table 9 with the correct answer in bold and italics as before. A bargraph of the percentage of correct answers received to these questions is supplied in Figure 7.

TABLE 9

Percentage of students responding to each choice of the questions on Metallic Bonding

Questions	Percentage of all students N = 110 a	b	c	d
				
1. If this metal were magnesium, do the individual spheres represent				
a) magnesium atoms	38			
b) magnesium 2+ ions		*43*		
c) magnesium nuclei with no electrons			19	
2. How would you explain the force holding the metal atoms in this crystal ? The attraction between				
a) metal atoms and their loosely -held electrons	10			
b) positive metal ions and their loosely-held electrons		13		
c) positive metal ions and the 'free' electron pool formed from the valence electrons donated by each atom			*51*	
d) positive metal nuclei and the 'free' electron pool formed from all the electrons donated by each atom				26

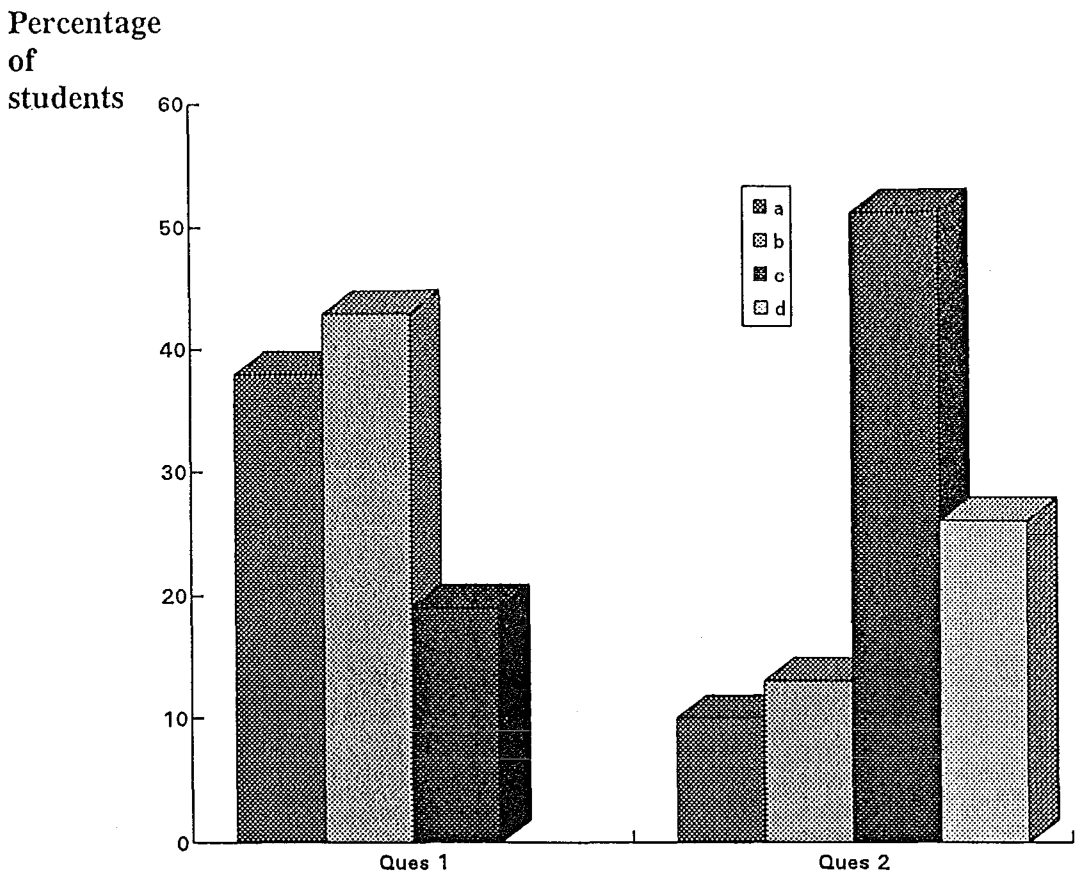


FIGURE 7: The percentage of students responding to each choice of questions about Metallic Bonding

These scores came as a quite surprise to the writer. Only one class has more than 50% of the students responding correctly to both questions. The 'positive metal ion - electron pool' model was considered to be commonly used by teachers, and well accepted by students. Metal structure is introduced to some extent in Form 5 if not earlier, and explained in more detail in this topic in Form 6. Table 10 provides the class percentages of correct answers.

TABLE 10 **Percentage correct responses by classes for the questions about Metallic Bonding**

Ques	Class W1	Class W2	Class X1	Class X2	Class Y	Class Z
D.1	43	65	67	22	50	11
D.2	43	50	73	33	66	50
n	*21*	*20*	*15*	*18*	*18*	*18*

The class results are more variable in this section; class W2 performing better than class W1 and class X2 performing significantly worse than class X1. The results from class Z were most inconsistent. Individual anomalies here, that is, one correct and one incorrect response were used as one of the indicators in choosing which students to interview.

(e) <u>Section E: Molecular Bonding</u> In this section on Molecular Bonding, the questions dealt with the nature and strength of intermolecular and intramolecular bonds. Questions 1 and 3 were multiple choice; questions 2,4,5 and 6 were either/or and question 7 involved a brief explanation.
The model referred to in the questions is presented below as Figure 8.

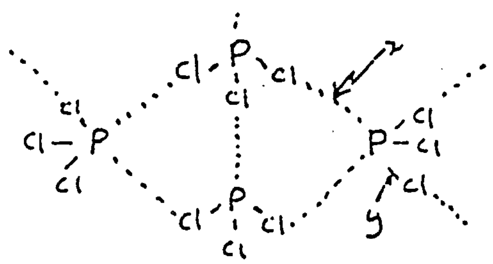


FIGURE 8: A diagram of a molecular substance, PCl_3 in the solid state.

Table 11 shows the percentage of responses to questions 1 - 4 about molecular bonding.

TABLE 11

Percentage of students responding to each choice of questions 1 - 4 about Molecular Bonding

Questions	Percentage of all students N = 110 a	b	c	d
1. In this model are the bonds marked x				
a) polar covalent	15			
b) ionic		9		
c) non-polar covalent			13	
d) Van der Waals				***63***
2. Are these same bonds				
a) intermolecular - between the molecules	***91***			
b) intramolecular - within the molecules		9		
3. Are the bonds marked y				
a) polar covalent	***61***			
b) ionic		21		
c) non-polar covalent			14	
d) Van der Waals				4
4. Are these same bonds				
a) intermolecular - between the molecules	13			
b) intramolecular - within the molecules		***87***		

In question 5, 90% of the students correctly identified the bonds marked 'y' as the strongest, and 85 % realised in question 6 that the bonds marked 'x' would break first. Only 19% of all the students recognised that PCl_3 molecules was most likely to be released as a gas.

Figure 9 shows the percentage correct responses given to all seven questions of this section.

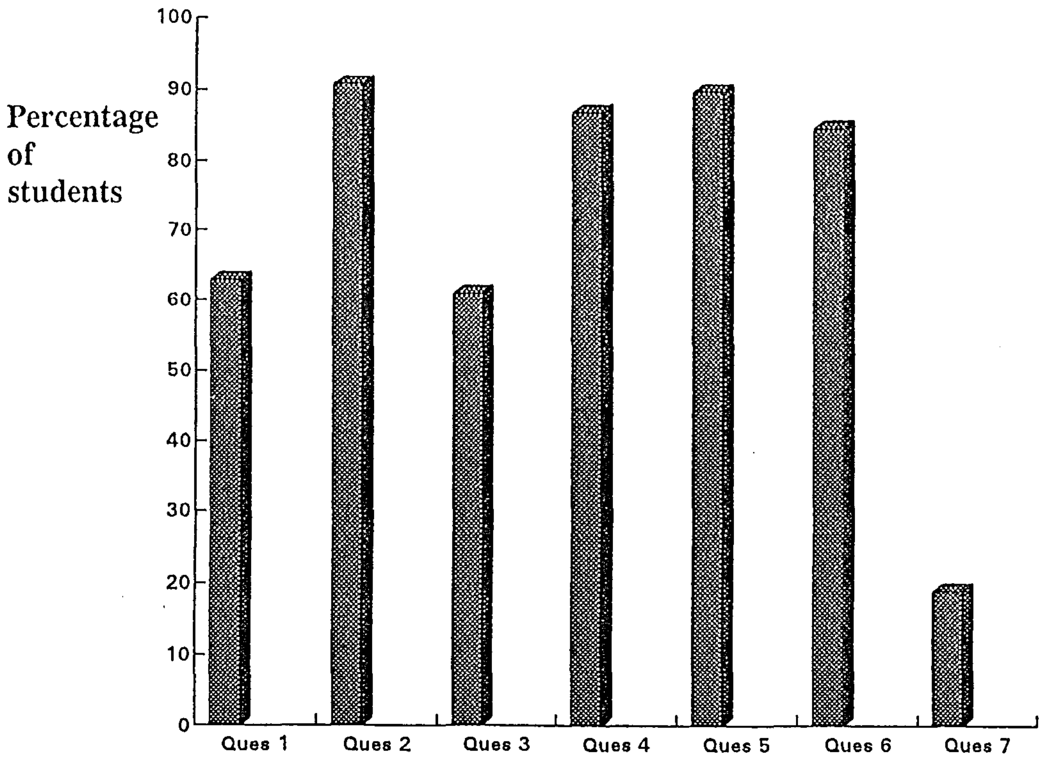


FIGURE 9: The percentage of students responding correctly to each question about Molecular Bonding

Table 12 is a class breakdown of the correct answers to all questions of this section.

TABLE 12

Percentage correct responses by classes for questions 1 to 7 about Molecular Bonding

Ques	Class W1	Class W2	Class X1	Class X2	Class Y	Class Z
E.i	71	50	80	83	88	11
E.ii	90	90	100	94	100	72
E.iii	33	30	53	61	88	83
E.iv	90	80	100	94	88	72
E.v	86	85	93	94	100	83
E.vi	86	90	66	83	100	72
E.vii	9	15	27	22	33	11
n	*21*	*20*	*15*	*18*	*18*	*18*

These results indicate the students were well aware of the difference between intermolecular and intramolecular bonding, although the diagram would have given a fair bit of assistance. The students had more difficulty identifying the nature of both bonds. The two classes of school W had particular trouble with the polar covalent intramolecular bonds of question 3, but the two classes of school X also did more poorly on that question. the results from Class Y were outstanding. Class Z did well in all questions except question 1, where most students answered non-polar covalent instead of Van der Waals. However it is the last question in this section on the behaviour of molecules on vapourisation that appears to be very poorly understood across all classes. It is worth listing the types of particles that the students included;

Cl_2	**HCl**
Cl^- ions	**P**
Cl^- particles	**PCl**
Cl	**P + Cl**
Cl_3	**Dust !**

Cl_2 was the most common and the 'dust' was from one obviously confused student. This ties in with the misconception noted by Treagust (1986) that 'covalent bonds are broken when a substance changes state'. This misconception was therefore examined in more detail during the student and teacher interviews.

(f) **Section F: Covalent Networks** This section on giant covalent network substances consisted of two questions. The first was a simple one-response question dealing with the nature of the particles in the network, while the second was multi-choice about the nature of the bonds between the particles. As with the molecular bonding section a diagram was provided and is reproduced below as Figure 10.

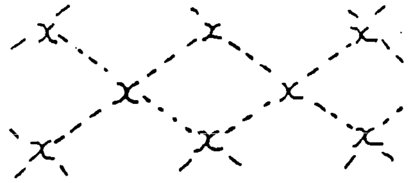


FIGURE 10: A diagram of diamond, a giant covalent network substance.

In response to the question about the nature of the particle represented by x in the diagram, 54% correctly wrote atom or carbon atom, while another 31% simply answered carbon. This is technically correct but not the answer to the question asked.

Table 13 presents the percentage of responses to question 2.

TABLE 13

Percentage of students responding to each choice of question 2 about Covalent Networks

Questions	Percentage of all students N = 110 a	b	c	d
2. What kind of bond is there between the x's ?				
a) polar covalent	31			
b) ionic		8		
c) non-polar covalent			***52***	
d) Van der Waals				9

If the 31% who answered 'carbon is added to the 52% who used the correct term 'carbon atom', 83% would appear to have a reasonable understanding that the particles in a covalent network were atoms. Again, as in the molecular bonding area, students had more trouble identifying the nature of the bonds (52%). In each of these three multi-choice questions on the nature of bonding (Section E, ii and iv and Section F, question 2), exactly the same choices were given in the same sequence. The fact that between 40 and 50% failed to correctly identify the bonds in each case is not so unexpected at this level, as the concepts are difficult and a fair degree of recall would be required. It is significant that in the class breakdown for question 2 of this section, none of the classes scored very well, but classes X1, X2 and Y were substantially better than the others for the question on the nature of the bonding. This can be seen in Table 13 at the end of the next section.

(g) <u>Section G: Ionic Bonding</u> In this section on Ionic Bonding, the first questions asked for three separate yes or no responses. The answer to the first two parts is negative, and the third is positive. The percentage of correct results is given in Table 14.

TABLE 14

Percentage of students responding correctly to the three parts of question 1 about Ionic Bonding

Question	Percentage of all students N = 110
1. Can ionic bonds occur between	
a) two metals	***65***
b) two non-metals	***64***
c) a metal and a non-metal	***79***

The second question asked the student to draw a diagram. This was completed by less than half of the students as some apparently ran out of time. Of those who did attempt it, 59% drew an acceptable representation of what was required.

It is significant that 35% of the students appear to believe that ionic bonding can occur between two metals, as well as between two non-metals. Ionic bonds form between oppositely-charged ions. Since all metals form positive ions and the non-metals form negative ions it is impossible for such bonds to form between two different metals or between two different non-metals. In the interviews the students appeared quite aware that ionic networks formed with alternating positive and negative ions. So the more probable explanation for the mistake is that they did not realise that metals only form positive ions and non-metals only form negative ions. This would tie in with their answers to Section B, question 4, in which many felt that atoms can form positive ions in one reaction and negative ions in another. The understanding of ionic bonding was also an interview topic.

Figure 11 shows the percentage of correct responses to both the two covalent network questions of Section F and the two ionic network questions of Section G.

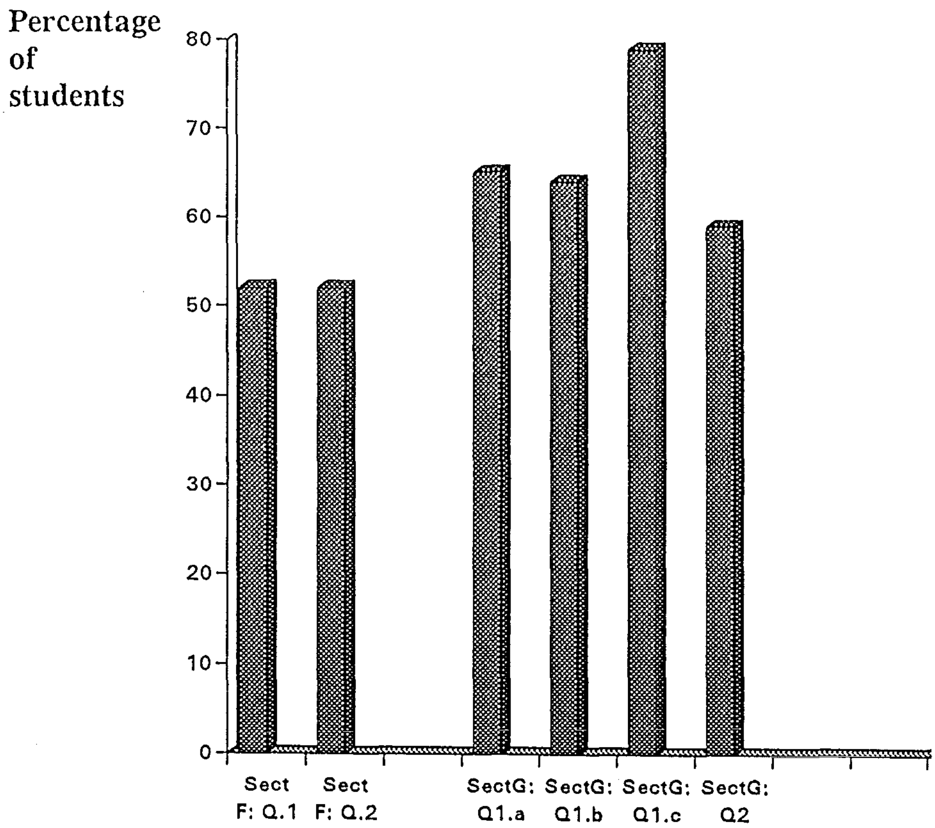


FIGURE 11: The percentage of students responding correctly to the two questions about Covalent Networks and the two about Ionic Bonding

Table 15 is the class breakdown of the correct answers in both these areas.

TABLE 15

Percentage correct responses by classes for the two questions about Covalent Bonding and the two questions about Ionic Bonding

Ques	Class W1	Class W2	Class X1	Class X2	Class Y	Class Z
F.1	38	20	27	22	22	17
F.2	29	35	67	66	72	33
G.1 (a)	76	57	53	44	88	66
(b)	86	50	53	50	94	50
(c)	81	65	80	77	88	77
G.2	19	25	33	50	61	0
n	*21*	*20*	*15*	*18*	*18*	*18*

As mentioned earlier, the poorer result of question F1 is due to many of the students answering carbon when asked to identify the type of particle. This is another language problem as a teacher would expect atom, ion or molecule when asked for a type of particle; students apparently feel if they can identify the atom that is enough. This example of 'looseness' occurred across all classes.

In analysing the class breakdown here, it is noticeable that class W1 scored better than usual on the ionic bonding questions. Class Y again scored highly. Not too much reliance can be placed on the overall knowledge base of question the question that for a diagram of an ionic network; few students attempted it, apparently from lack of time.

(h) <u>Section H: Bonding In General</u> This was the final area of the questionnaire. It consisted of four statements, two on the nature of bonding, and two on the types of particles present in a compound. The students were asked whether they agreed or disagreed with the statement and then to give a reason. It was disappointing that the majority of the students simply agreed or disagreed with the statements, as the real purpose was to analyse their reasoning. The percentages given were the correct responses of those who answered. Some interesting misconceptions were uncovered.

i) The first statement was

All bonding is electrical in nature.

Only 48% correctly agreed, and these were some of the misconceptions that stood out:

'No, some bonds are caused by chemical reactions'

'No, some bonds are polar'

'No, because a lot of things have no charge'

'No, there can be gas bonds without electricity'

'No, its the need to fill the valence shell'

'No, because of ion-sharing' (a new phenomenon!)

'No, they're all electrical except Van der Waals'

Obviously there are some strange ideas about bonding. The electrical nature of bonding was introduced in the interviews whether the student had commented or not. Unfortunately it was not possible to follow up on all of the above statements, but this was done where they had been made by one of the twenty students interviewed.

ii) The second statement was

Van der Waals bonds are much weaker than covalent bonds

69% correctly agreed and this tied in well with the results from Section E of the questionnaire on Molecular Bonding. There it was apparent that a good majority of the students were able to distinguish correctly between intermolecular and intramolecular bonding.

c) The third was

All compounds that contain a metal are composed of ions

In their experience, the students would be correct to agree, and 62 % did. The few reasons given that revealed misconceptions were related to those already shown in the discussion of Section D on metallic bonding.

d) The fourth and last statement was difficult to follow

All compounds that do not contain a metal are composed of molecules

Here few reasons were given. 58% identified of those that answered correctly stated it was incorrect, but even then, some of them did so for the wrong reason. Such comments as

'No, everything contains molecules'

'No, all compounds are formed by molecules, whether metal or non-metal'

'Metals and molecules are the same thing'

reveal a misconception about the existence of 'metal molecules'. This misconception also showed up in the analysis of the answers to question 6 of Section B, where the students were asked to indicate the interrelationships between atoms, molecules and ions. As a result, both the relationship between molecules and compounds, and formation of ionic compounds were chosen as interview topics.

4. METHOD FOR THE STUDENT INTERVIEWS

(1) How The Areas For Interview Were Selected

When the results of the questionnaire were analysed, there was no shortage of misconceptions. However, some of the misconceptions appeared more frequently than others, and some of the misconceptions caused problems in more than one area. With these considerations, the following areas were chosen as topics for the interviews.

(a) **Elements and Compounds versus Atoms, Molecules and Ions** Misconceptions that appeared in section A and B on atoms and ions are included under this heading. Question 6 of section B on the relationship between pure substances and their particles was included due to the previously discussed tendency to mix macroscopic and sub-microscopic terms.

(b) **Metallic Bonding** Section D was chosen as there were substantial problems with the identification of the metal structure and the nature of metallic bonding.

(c) **Molecular Bonding** Part E was chosen as the very low percent of correct responses to question vii indicated a serious problem with the understanding of vaporisation even though the difference between intermolecular and intramolecular bonding appeared to be fairly well understood, unlike the results reported by Peterson and others (1986).

(d) **Ionic Bonding** Question 1 of Part G was used as there were substantial problems with the nature of the ions in the network. It was also decided to follow up on the work of Taber (1994) on the formation of ionic networks.

(e) **The Electrical Nature of Bonding** Statement 1 of Section H was chosen as the reasons given for agreeing or disagreeing chiefly with statement A on the electrical nature of bonding revealed misconceptions in this area.
As explained earlier, the misconceptions revealed by the other three statements in this section will be discussed with the related section.

(2) How The Students Were Chosen

The students to be interviewed were chosen from an analysis of the questionnaires. The interest for the research lay in determining the misconceptions that the average student might have, so the marks were first totalled to give some indication of ability. Very high achieving students and those who had done very little on the paper were not considered further. The second step was to examine the remaining papers for anomalous answers in the areas chosen for the interview. In addition, most of the students chosen to interview had included some comments in the final section of the questionnaire, Section H on Bonding.

When a short list of six students per class was drawn up, the teacher was asked to approach the students to determine if they would consent to being interviewed. Once three willing students were obtained, a suitable time to carry out a fifteen-to-twenty minute private interview with each student was arranged. Before commencing the interview permission forms were discussed with each student and their signature was obtained.

The permission slip also covered their agreement to be re-interviewed at a later date. A copy of the student permission form is included in Appendix B.

(3) How The Interviews Were Carried Out

It was decided to focus the interviews on the five areas listed, and some cards and models to stimulate discussion in these areas were prepared. The models used are shown in the photographs on page 40.

* For topic (a), *Elements and Compounds versus Atoms, Ions and Molecules*, cards of the five terms were prepared for discussion of the inter-relationship of the terms. The cards served as a type of concept map as the students were asked to choose what they considered was the most cental term, and then to explain its relationship to the other four terms. Concept mapping is a technique described in 1984 by Novak and Gowin in which students are asked to arrange a set of cards or terms in a pattern of their own choice, and then to draw lines between related terms and explain the relationship on the lines. In the interviews, the students were simply asked to arrange the cards, and the relationships were explained verbally. Misconceptions about the atomic subparticles and ion formation were discussed without models.
* For topic (b) on *Metallic Bonding* small black spheres that could be affixed by the student to marked sites on a piece of card were used, thus forming a modified grid. This model is shown in Figure 12.
* For topic (c) on *Molecular Bonding*, a three-dimensional model of three trigonal-pyramidal molecules joined by thin wire were prepared to use with the discussion of molecular bonding. The molecules could represent either Phosphorous trichloride, PCl_3, which was the molecular substance

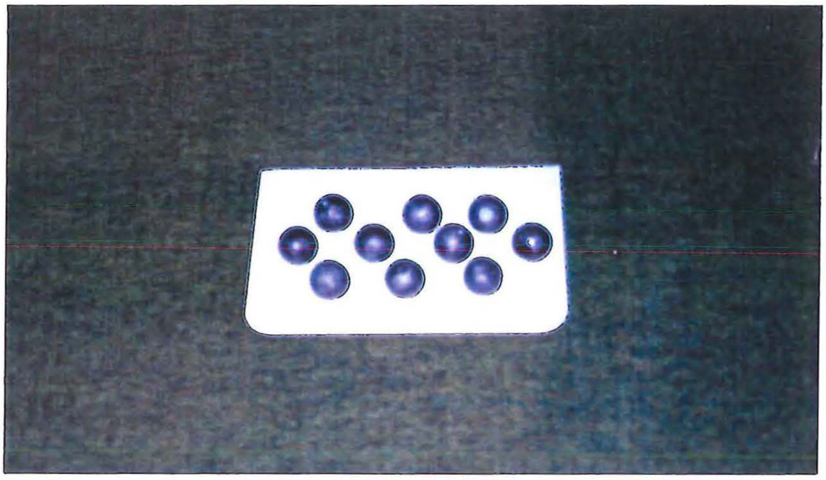


FIGURE 12: The construction model used in the interviews when discussing Metallic Bonding

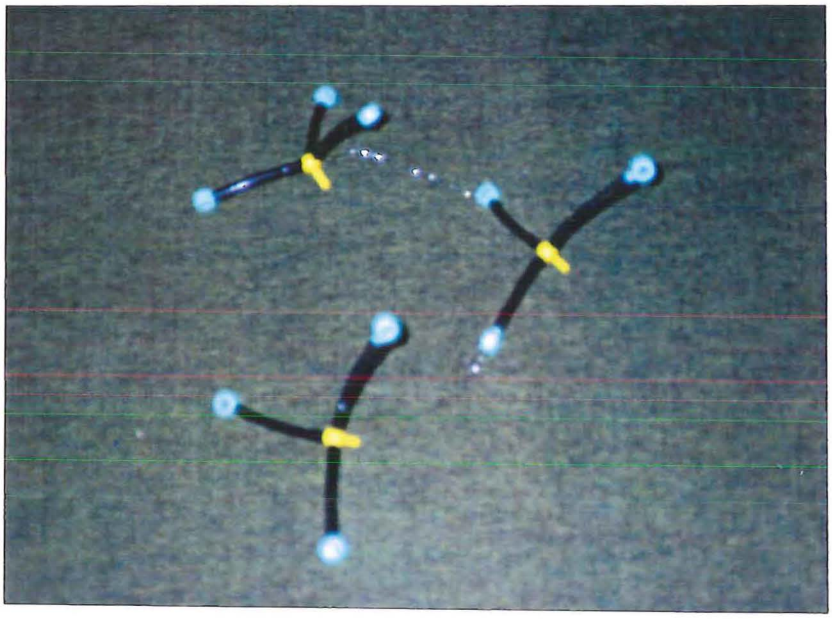


FIGURE 13: The model used in the interviews when discussing Molecular Bonding

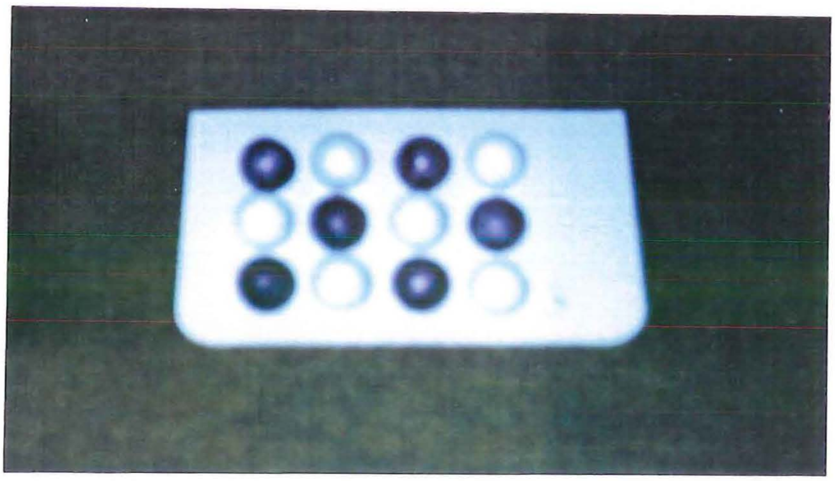


FIGURE 14: The construction model used in the interviews when discussing Ionic Bonding

used on the questionnaire, or ammonia, NH_3 a molecular substance much more familiar to the students. This model is pictured in Figure 13.

* For topic (d), *Ionic Bonding*, small black and white spheres were used on a grid similar to that used when discussing metallic bonding. This model is pictured in Figure 14.

The general statement on the electrical nature of bonding (Section H) was also discussed without models.

With the student's permission all the interviews were taped in full. The interviews lasted between 15 and 20 minutes and in most cases took place over a lunch period.

5. RESULTS OF THE STUDENTS INTERVIEWS

Each of the five interview issues listed will be treated in turn. Sections from the transcripts of the interviews are used to demonstrate the misconceptions that were found. In the sections used, T stands for Teacher/Interviewer. Each student has been given a code name, and the first initial of the code name is used in the transcripts. There is a short summary of the misconceptions demonstrated under each set of interviews, but the implications of the findings will be treated in the discussion.

(a) Elements and Compounds versus Atoms, Molecules and Ions As noted above, a set of small cards - one for each of the five terms: atoms, ions, molecules, elements and compounds were used with this part of the interview. In the first interview the student was asked to arrange them so that the most central term, in their opinion, was placed in the middle. They were then asked the relationship between this term and the other four.

The discussion in this part of the interview was to be based on the student's responses on the questionnaire to question 6 of section B. As the interviews progressed, however it was found that discussion of ionic networks revealed several misconceptions about molecule formation, as did a few of the statements that the students had made at the end of the paper about bonding in general. All these related misconceptions will be included in this section as well. The following misconceptions are treated in turn:

i) Molecules are particles of elements only

- metal molecules

- molecules for all elements

ii) The number of protons of an atom can change

iii) Electrons from the inner energy levels of an atom change in a chemical reaction.

iv) Ions combine to form molecules

v) The terms atoms and elements; and molecules and compounds are synonymous.

i) **Molecules are particles of elements only.** Molecules can be made up of elements , such as H_2, Hydrogen gas or O_2, oxygen. But molecules are also the smallest particles of molecular substances, such as H_2O, water, NH_3, ammonia and C_2H_5OH, ethanol. Kelly, however, was quite sure that the term molecules could only be applied to elements.

K: *A molecule has only got one type of atom, like H_2, whereas a compound has more than one...*

But this led her into more problems with ions

T: And what about ions in compounds ?

K: *Compounds are mixtures of ions or groups of ions*

T: So what would you say water is ?

K: *A compound*

T: And would it have ions ?

K: *Yep, H^+ and OH^-*

T: And what about ammonia, NH_3 ? Does it have ions ?

K. (Pause)...*No..o..so its a compound that doesn't have ions ? Its a compound...its just the formula...Is it a molecule ?*

T: You told me molecules could only be of one kind of atom only, like H_2....

K: *Yeh, so I'd just say it (ammonia) was a compound...*

So did Peter.

T: How does a molecule relate to all these other terms ?

P: *A molecule is made up of the same type of atoms...*

T: So you think you can only have molecules of elements, you wouldn't have molecules of compounds...?

P: *Yeh, just elements like* O_2

And both of them thought there are metal molecules too.

K: *Well,* Mg_2*..if you've got a molecule that just two of the same type of metal atoms*

T: So there is a molecule of magnesium...

K: *Yep*

T: And a molecule of aluminium ?

K: *Yep*

T: And a molecule of sodium ?

K: *Yeh...No...I'm not sure about a molecule of Na....maybe metals don't have molecules....*

Peter thought all elements form molecules

P: *An element is made up of a whole lot of molecules*

T: Can you give me an example ?

P: *Hydrogen gas*

T: Do you think every element is made up of molecules ?

P: *Yes...I'd say yes*

T: Well, what about the element magnesium...is it made up of molecules ?

P: *Yes*

T: And Helium gas...is that made up of molecules ?

P: *Yes*

(Not 'incorrect' as there are textbooks that refer to the monoatomic 'molecule' of Helium, for example Metcalfe (1970)).

Kelly and Peter are restricting the use of the term molecules to elements only but then erroneously expanding it to include all elements. These are not common misconceptions at this level, but do indicate the range of problems dealing with the word molecules.

ii) The number of protons of an atom can change. This is an area where misconceptions could be foreseen. The number of protons in the nucleus only changes in nuclear reactions; either the element itself or its isotope(s) are radioactive, or a stable nucleus is bombarded to cause its breakdown. In these cases the original element is changed into another element. It never happens in ordinary chemical reactions.

Joan answered on the questionnaire that the number of protons may change when an atom becomes an ion.

T: When an atom forms from an ion are the protons ever involved ?

J: *Yes, I suppose so*

T: You think so...the atoms gain or lose protons when they form ions ?

J: *Well...they do when its an isotope...*

She thinks that atoms gain or lose protons to become isotopes in the same way they gain or lose electrons to become ions. Isotopes are introduced at Form 5 but the full explanation about how they form from nuclear disintegration of atoms is left until Form 7. As only 80% of the students correctly answered this basic question on the questionnaire, it is likely that more shared Joan's misconception.

iii) Electrons from the inner energy levels of an atom change in a chemical reaction. In school X, four students (out of 33) stated that *in some cases* the inner energy level are affected by the gain or loss of electrons in a chemical reaction. This is correct for transition elements but they are not introduced until Form 7. Therefore the expected answer was *never true.* However when the students were questioned about it they indicated why.

T: (For this statement) you put 'true in some cases'..can you give me a reason ?

D: *I was thinking of ionisation energy, see, it is possible to remove electrons from inner levels but I don't know if its possible in a chemical reaction...*

and

T: (For this statement) you put 'true in some cases'..can you tell me what happens ?

R: *Well, you can remove electrons and it gets harder and harder to take them off....its called ionisation energy*

T: But is that a chemical reaction ?

R: *I'm not sure.....*

The topic of ionisation energy is usually left until the seventh form.

iv) Ions combine to form molecules In analysing the questionnaires, 9% of the students stated that 'ions are the simplest units of all molecules' or 'ions can combine chemically to form molecules'. In the interviews this was discussed, even though the students may not have made the statement. Cindy was in the upper quartile of her class.

T: So what is a molecule ?

C: *Positive and negative ions coming together....*

Even the rest of the year's work and a final exam did not shift her position. In the second interview:

T: What about the molecules ?

C: *They're when ions are joined together to form compounds*

T: What are the actual bonds within the molecule ?

C: *Ionic*

T: What about H_2O ? Is that ionic ?

C: *Yeh*

T: And NH_3 ? Is that ionic ?

C: *Yeh..*

T: What makes you think they're ionic ?

C: *Well, the H is a positive ion and the N has a three negative charge...*

T: What about the shared electron pairs...do they come into the picture ?

C: *Yeh...when they're polar...*

Lucy put it in reverse:

L: *Compounds are made up of molecules*

T: Where do the ions come in ?

L: *Ions make up the molecules...*

And Darren

T: (repeating Darren's statement) All compounds form from ions....?

D: *Yes, they do...*

T: What about ammonia ?

D: *Ammonia...yeh...that's got hydrogen ions in it...that's got ammonium ions as well*

and Jack had the same idea :

T: Is there a relationship between ions and molecules ?

J: *Yes..ions can form molecules, like you could have a sodium ion and an hydroxide ion and they could form a sodium hydroxide molecule*

Kelly used water as her example.

T: What about the relationship between molecules and ions ?

K: *Um...thinking of water and do you mean molecules don't contain ions ?*

T: What do you think ?

K: *Well, with water you've got the* H^+ *and the* OH^-

T: When do you get those ?

K: *Um...*

T: When you have water vapour, do you still have H^+ and OH^-?

K: *Yeh...*

One quarter of the interviewed students demonstrated this misconception. They have not realised that there is no direct transfer of an electron from one atom to another when ions form. This misconception and how it arises was discussed with the teachers, and will also be reviewed in the discussion.

v) <u>The terms atoms and elements; and molecules and compounds are synonymous.</u> This was never a statement made by the students, but due to the number of instances of mixing the terms in the questionnaire the issue was included in the interview.

Cynthia illustrates the point. Her questionnaire contained the statement 'Elements gain or lose electrons to form ions'.

T: What is the relationship between atoms and molecules ?

C: *Elements are made up of atoms and molecules are different atoms joined together by chemical bonds and compounds are the same as molecules...one of them has a certain number of elements...I'm not sure if its molecules or compounds*

Jacky shows a similar lack of precision in using terms.

T: Can you give me an example of a molecule ?

J: *No...I can't think of one*

T: What about water ? Its not an atom, is it ?

J: *Yes, that's a type of compound...it must be a molecule..*

Cindy is another example

T: On your paper you said 'Elements can combine chemically to form molecules'... is there a better way to word that statement ?

C: *Atoms....*

T: Why did you put elements then ?

C: *Oh...elements and atoms....they're all on the Periodic Table*

These answers reinforced the impression from the questionnaire that the problem was not one of misconceptionn, but more a lack of precision with language. This difficulty was raised in the interviews with the teachers.

(b) <u>Metallic Bonding</u> After analysing the questionnaires it was decided to provide material in the interviews for students to construct a model. The material was very simple; some black polystyrene balls and a blue-tack base, but it gave students time to collect their thoughts about metal structure. It is realised that the actual metal structure is very complicated and that makes it difficult to explain. A standard line used in many texts is to compare the structure to 'positive ions in a sea of electrons', that is, the metal ions lose their valence electrons which form a pool of electrons to be equally shared by all the positive ions. The merit of this model is that it can be used to explain various metal properties. While it is not completely accurate, it is generally considered closer to the actual situation than the other options supplied in the questionnaire. It is a section that is usually covered to some extent in Form 5.

The interviews uncovered some further surprises, but all were concerned with the model.

Kylie felt both positive and negative ions were present.

T: (Pointing to model) What do those black spheres represent, atoms, molecules or ions ?

K: *Molecules*

T: And do you think they would have a charge ?

K: *There's something about a sea....that's right a sea of electrons...positive and negative ions in a sea of electrons*

T: So are the black spheres molecules or ions ?

K: *Ions*

T: Are there both kinds of ions or just one ?

K: *Either kind...*

Cynthia didn't know what happened to the electrons.

T: If they're ions what kind of ions are they ?

C: Mg^{2+} (the metal in the model was called magnesium)

T: So what happened to the electrons ?

C: *They're lost*

T: Where ?

C: *I....I don't know*

Jacky had similar problems

T: Do you think those are atoms or ions ?

J: *Ions*

T: OK ..What happens to their extra electrons

J: *They go off and find other partners*

T: Do they ?

J: *They do something anyway...They go off into the outer shell or something*

Peter had the same problem

T: Can you tell me about the structure of a metal ? Are the atoms sort of stuck together ?

P: *The electrons are able to move around freely....*

T: They move freely ...around what ?

P: *The atoms...*

T: The atoms...so where do the electrons come from ?

P: *They come from the atoms....*

T: Well, which ones are coming off the atoms ?

P: *The spare ones...Oh, .. I'm not sure really...they just lose, I know they lose because we call them 'losers'...all metals are 'born losers'*

Darren also had trouble with the structure, but figured it out during the interview;

T: Now in this model what do the black spheres represent ?

D: *They are atoms...*

T: Atoms

D: *No, molecules...*

T: And what else can you tell me about metal structure ?

D: *Just the current ..*

T: The current is electrons ?

D: *Oh..h...they're ions !*

T: Why did you change to ions ?

D: *Because ions have charges....outside*

T: So where are the electrons

D: *The electrons are outside the ions...that's the negative charge then* ?

T: So where do the electrons come from ?

D: *Their outer shells....*

And Jill had trouble with the term 'metallic bond'

T: Are these atoms, or ions or molecules or what ?

J: *Atoms*

T: So what do you think of when you think of a metallic bond ?

J: *A bond between two metals .....*

Don revealed some of the problems of an over-simplified model.

T: If this is magnesium metal, what do you think the circles represent ?

D: *From my understanding, that would represent the nucleus .....and I'm not sure....I'm not sure whether the outer electrons are involved... Well, if its magnesium, these could be 2^+ ions and they'd give away two electrons to the pool in between...but does that mean this one in here with the electrons floating around...they can get charged or something..just temporarily ?*

because the electrons are moving around..say, for example, you've got two electrons over here and they slide over here, and leave that ion without enough electrons around it...Does that happen ?

and later

D: *Wouldn't each Mg^{2+} just attract its own electrons though ?*

These interviews back up the findings of the questionnaire that the simple 'positive ion-electron sea' model has not helped many students to make sense of metallic bonds.There was much confusion both about the particles in the metallic network and the source of the electrons. These difficulties are also discussed with the teachers in their interviews and will be reviewed in the discussion.

(c) Molecular Bonding Molecules consist of atoms held together by covalent bonds. In a covalent bond an electron pair is shared between adjacent atoms so that each atom effectively has a 'complete' valence shell. Molecules are uncharged, and the covalent bonds between the atoms involved are very strong. They may be made up of two or more atoms; many non-metal elements form molecules, such as H_2, O_2, S_8 , but most molecules are the units of compounds, such as CH_4 and H_2O.

Most of the molecular compounds dealt with in Form 6 are gases at room temperature, and it is not always easy for students to visualise what they are like as solids. As solids the individual molecules are held together by intermolecular bonds called Van der Waals forces, which are much weaker than the strong intra-molecular covalent bonds.

Covalent bonds are usually introduced in Form 5, but Van der Waals forces and the structure of molecular solids is covered in this unit in Form 6. In analysing this section of the questionnaire it was found that there was a very high percentage of correct answers for the theoretical questions (Ei-vi) but a extremely low result (17%) when an application of the theory was introduced. A model of a few simple kitset NH_3 molecules joined by thin wire to simulate the inter-molecular bonds was prepared for use in the interviews.

There were two main reasons for the incorrect answers to this question. Only the first is a misconception.

i) **The intra-molecular bonds break when a molecular solid becomes a gas.**

ii) **Heating a substance that contained chlorine might cause the release of chlorine gas.**

Each of these reasons will be dealt with in turn.

i) **<u>The intra-molecular bonds break when a molecular solid becomes a gas</u>**. This turned out to be the major reason of those interviewed. The following two examples are chosen from twelve very similar transcripts. It was found during the interviews with these students that some were able to recognise their own misconception.

Kylie was the first to do so in her first interview.

T: This is a model of solid ammonia. Can you tell me what is going to happen as I heat it up ?

K: *Well, the bonds in between (intermolecular) will break first...*

T: And I keep on heating it and it turns into a gas

K: *And then the bonds inside (intramolecular) would break and nitrogen and the hydrogens would go off...*

T: So if I had ammonia gas I'd have nitrogen and hydrogen ?

K: *No...o...If it stays ammonia they can't break, because if it were hydrogen it wouldn't be ammonia*

T: A new thought

K: *Yea....it certainly is*

But the knowledge didn't last in her case. In her second interview at the end of the year she had reverted to her previous model.

T: So if I continued to heat this up, what would go off into the atmosphere ?

K: *The H's*

T: Just the H's ?

K: *And the N...*

T: So once this becomes a gas these molecules all break up do they ?

K: *Yes*

T: So what's the smell of ammonia due to ?

K: *The breaking of the bonds....I dunno....Do they reform again?*

Jacky felt the smell was due to nitrogen in her first interview, but she saw the problem and remembered it at the end of the year.

T: If I heat it up and make a gas out of it, what happens ?

J: *Well, first those in-between bonds break and then.....do the bonds in the actual molecule begin to break ?*

T: What do you think ?

J: *Yea, they do*

T: So what sort of a gas would it make ?

J: *Hydrogen*

T: Hydrogen ?

J: *And Nitrogen*

T: If you smelt ammonia then, what would it be due to ?

J: *It would be the Nitrogen*

T: It would be the Nitrogen smell.....No...It couldn't be Nitrogen because it doesn't smell.....those bonds don't break, do they ?

And her second interview:

T: So when this becomes a gas, do these bonds break ?

J: *No...*

T: Do you remember when you figured that out

J: *It was the last time when we had ammonia...because if you can smell it the molecules can't break*

Sue, an able student, put it more clearly

T: As I heat it up which bonds will break first ?

S: *The bonds in between the molecules*

T: Now I'm going to turn it into a gas...

S: *Some of the bonds within the molecule will break......I think..*

T: Not sure ?

S: *Yes...I don't think that's right...*

T: What's the problem ?

S: *Its not actually going to be ammonia if the bonds within the molecules break....so just those ones (inter) would break and the molecules would separate...*

T: You hadn't thought of that before ?

S: *No, its just come now when I realised the bonds in the molecule would have to stay for it to be ammonia...*

The fact that twelve students out of twenty students demonstrated this misconception when interviewed shows the extent of this problem. This idea that a substance completely disintegrates when it forms a gas can probably be traced to introductory teaching about particles. This is another teacher-interview discussion topic and is also evaluated in the discussion.

ii) Heating a substance that contained chlorine might cause the release of chlorine gas. PCl_3 was chosen because its structure was closely related to ammonia which is used so frequently in teaching this section. The use of PCl_3, however, an unfamiliar substance, led some more capable students to suggest that chlorine gas would come off, which can occur, albeit rarely, when a compound containing chlorine is involved. To avoid this problem ammonia was used in the interviews.

Carol's interview was similar to two others who mentioned this problem.

T: (If I keep on heating ammonia) what goes in to the gas phase ?

C: *The....molecules*

T: So even if it goes into the gas phase these molecules don't break up ?

C: *No*

T: You're sure

C: *Um....*

T: Well, with PCl_3 on this paper you told me that Cl_2 particles went into the gas phase...and its very similar to NH_3. Can you remember why you said that ?

C: *Well, probably because I thought chlorine was a gas and I didn't know anything about the P and so I just thought well, if its a vapour it must be chlorine*

This confusion was only found in students interviewed later in the year indicating a greater familiarity with laboratory work.

(d) Ionic Bonding The section on ionic bonding came at the end of the paper and about 25% of the students did not complete it. However, the results indicated some problems. 10% of those that did answer stated either that

Ions are the simplest units of all molecules

or

Ions can combine chemically to form molecules.

so material was provided for the students to construct a model. The material was very similar to that used with the metal section; some black and white polystyrene balls and a blue-tack base. The results uncovered a surprising misconception about the formation of an ionic network.

Ruth explains.

T: Say these are ions of sodium and chlorine..can you make a model for me on this base ?

R: *They form an ionic lattice*

T: Does a unit of NaCl come in (into the lattice) together or does the lattice just form from a lot of separate ions ?

R: *Initially one and one came together*

T: So they were a pair before the lattice was formed ?

R: *Yep*

T: Well, once they were in the lattice, is that one still more attracted to the one it came in with than the others ?

R: *No*

Steve had the same idea.

T: Can you make me a model of NaCl and explain it as you do ?

S: *You put them alternating...a negative always surrounded by the positives...*

T: Do you think since the Na was positive and the Cl was negative that they formed a pair before they joined the lattice ?

S: *Yes...that's what I think, yea...*

T: So if they all came in as little pairs are they still more attracted to their former partner than to the others?

S: *No...they won't be..*

T: They won't be , but you still think of them....

S: *I still think of them as sort of like pairs....It works I suppose*

Seven of the interviewed students has the same idea, and two of them carried it further. Darren explained what he thought

T: So now its in the network, is this sodium attracted to that one still (the one it came in with according to Darren) or is it equally attracted to all of those around it ?

D: *Well...um...I think it would just be attracted to one of them*

T: You think this (sodium) will just be attracted to that (chlorine)

D: *Yeh...so they'd all be attracted to just one other...*

Jack went further and called the NaCl unit a molecule

T: What's the relationship between ions and molecules ?

J: *Well, when ions come together they form a molecule*

T: Like Cu^{2+} and SO_4^{2-} ?

J: *Yeh...as in salt...the* Na^+ *and the* Cl^-

T: So what happens when they form an ionic lattice ?

J: *They come into the ionic lattice together...*

T: So are they still more connected with each other than they are with any of the others..once the lattice forms ?

J: *No, they're equally connected now....they don't stay together...*

The problem here closely related to the previously-treated misconception that ions combine to form molecules. It follows that if there are 'ionic molecules' there must be an explanation for getting them into an ionic lattice. The teachers were asked to comment on this problem, and it will be reviewed in relation to the findings of Taber (1994) in the discussion.

(e) **<u>The Electrical Nature of Bonding</u>** As only 48% of the students had agreed with the statement that all bonding was electrical, this was brought up at each interview.

T: You don't think all bonding is electrical, Jill ?

J: *Well, covalent bonds aren't*

T: How would you describe a covalent bond ?

J: *Its that shared electron pair*

T: But what holds the electrons in place ?

J: *What's in the centre of them...the nucleus*

T: And what's in the nucleus ?

J: *Neutrons and...protons*

T: Do they have a charge ?

J: *Protons do....yeh, they're positive*

T: They're positive ?

J: *Oooooh..and the negative electrons..so its electrical after all!*

And Ruth

T: With the statement 'All bonding is electrical', you put 'No, they don't all conduct...

R: *I was in a big rush here....*

T: Well, do you think ionic bonds and covalent bonds are electrical ?

R: *Not covalent*

T: How do they work ?

R: *They share electron pairs.....well, I guess they are too.*

and Leslie

T: With the statement 'All bonding is electrical in nature' you disagreed and said that covalent bonds involved nothing electrical..they just share electrons'....How are the electrons being held by the atoms ?

L: *Well, they haven't got full (valence) shells, so when they share they become full....*

T: OK, but what's the force that holds the electrons ?

L: *The negative charges...Is it electrical ? Do the protons pull on the electrons ?*

In these examples it is not so much a misconception as a lack of any conception. It is clear that many students had simply not thought about bonding as electrical.

(5) **Additional Insights From Student Interviews**

In the course of the interviews it was quite often apparent that the students were frustrated by their own lack of understanding. Some of this frustration is caught in the following excerpts.
Lucy had incorrectly stated that the number of protons in the nucleus of an atom can change when an atom forms an ion.
T: Do they (the number of protons) change when you form an ion?

L: *Yes...I think it does*

T: Would you draw an oxygen atom for me ?

(She drew a standard diagram with the electrons circling the nucleus in layers)

T: So what happens when it forms an ion?

L: *It grabs two electrons*

T: And what happens to atoms that have very few electrons in that outer layer ?

L: *They lose electrons*

T: Do the protons in the nucleus ever change ?

L: *No*

T: No ?

L: *No*

T: You just remembered....so what was the confusion before ?

L: *Well, its just how you say it, or read it....*

T: The words ?

L: *Yeh, its just ions and electrons and protons and nucleuses and atoms and all of that...there's so much*

T: That's what they call the language of chemistry

L: *Yes..well, the language of chemistry is SO confusing..*

Christine had a similar complaint

C: *We had catalysts and stuff like that drummed into us, so when I'm writing about it I can understand it, but when they talk about ions and molecular bonds and molecules and all that stuff and they're not in the right sort of sentence, I just get all mixed up ....*

The language difficulty is well recognised in the literature as a major problem in teaching this material. There are a lot of new terms and their relationship to each other is not simple. But there is an additional complication here that most language teachers do not meet. Practically all the terms have been introduced to the students in previous years from a variety of teachers. For this reason the students often have somewhat different meanings for the terms and many feel they already know it. The problems created by this situation are discussed in the teacher interviews and revisited in the discussion.

6. METHOD FOR TEACHER INTERVIEWS

The teacher interviews took place after their students had completed the questionnaire, and the results for the classes had been collated. They were therefore familiar with the questionnaire and the interviews centered around the areas that the students had found most difficult. The interviews were less question-and-answer and more discussion about how the student misconceptions arise, what could be done to prevent them and the presentation of the topic. The opinions of the teachers on the language problems and timing of the topic in the school year also formed part of the interview.

7. RESULTS OF THE TEACHER INTERVIEWS

(1) Areas Of Student Misconceptions

Each of the five topics addressed in the student interviews were raised with the teachers and these will be discussed in turn.

(a) Elements and Compounds versus Atoms, Molecules and Ions The student interviews on Atoms and Ions had highlighted five areas in which there were misunderstandings about the use of these terms and their relationship to each other

i) Molecules are particles of elements only

- metal molecules

- molecules for all elements

ii) The number of protons of an atom can change in a chemical reaction

iii) Electrons from the inner energy levels of an atom change in a chemical reaction.

iv) Ions combine to form molecules

v) The terms atoms and elements; and molecules and compounds are synonymous

The teachers related the two misconceptions about molecules (i and iv) to the way the term is introduced. Most of the students arrive in Form 6 chemistry with some simple definition of all five terms, but these get easily confused. In the case of molecules the definition has often been so simplified that it is incorrect. The problem is that there are molecules of both compounds and elements, and ionic compounds do not form molecules. Thus a simple definition, such as 'A molecule is the smallest particle of a compound' is wrong. Teacher X2 pointed out

> 'In junior science a lot of people still teach ...that an atom is the smallest particle of an element and a molecule is the smallest particle of a compound'.... because that's what they've learned' ....You have to introduce these terms simply and its very difficult because you've not only got the molecules of compounds but you've got the molecules of the gaseous elements (H_2, O_2 etc)) and I'm very careful never to mention ionic compounds when I'm talking of molecules, but even without saying it you're still implying it (that they form molecules)...'

Teacher W1 clarified the issue;

> 'But the problem for science teachers is what to do with the gases, ...hydrogen is always H_2 and oxygen O_2..you have to say they're molecules, and then you've got molecules of compounds like methane, CH_4 and ethanol, C_2H_5OH which they do in Form 5....Its no wonder they think every compound has a molecule...and once learned'...

So the dilemma is to have junior science teachers introduce a simple and incorrect definition of a molecule to avoid confusion, or to start with a correct and complex definition, spelling out the exceptions, and create even greater problems of understanding. As teacher W put it:

'In chemistry everything is exceptions....Yes, I told you that yesterday, but this is an exception....and they get so confused so they're learning a science of exceptions all the time'.

The second misconception, - that the number of protons can change in a chemical reaction, was considered relatively common. It arises from the confusion of a chemical reaction with a nuclear reaction. As teacher W1 said

'It happens when you get to isotopes. They've been introduced in Form 5 and their structure is detailed again in Form 6, but they don't find out the way they form until Form 7. Its no wonder they put it together for themselves and figure that they just form in chemical reactions where the protons take off...its hard to check what they think when your rushing to introduce new material.'

The misconception that electrons in the inner energy levels take part in chemical reactions, arises either from confusing chemical reactions with the determination of ionisation energies, as was seen with interviews of students from one school, or simply from lack of thinking about it. This difficulty of getting students to 'grapple with chemistry until they get a clear understanding' (Teacher X1) will be considered in the discussion.

The last issue, that students have problems moving between the macroscopic terms of element and compound and the sub-microscopic terms of atom, ion and molecule came as no surprise to teachers. As Teacher Y put it,

'I see in my teaching now there are two groups...there's the group that is on top of it...they have the understanding and can toss around the terms and there's the other group that gradually gets further and further behind...who havent' got a clear understanding and just throw them (the terms) around'.

Teacher Z agreed.

'But the main problem is that they don't really think about the terms; many of them are quite content with relatively vague conceptions and their lack of understanding only hits them when they are faced with a point blank question'.

(b) Metallic Bonding The confusion the students displayed with the two questions on metallic bonding also struck a chord with the teachers. 47% of the students stated in question 1 that the spheres represented atoms. The correct answer was considered to be magnesium 2+ ions. In the second question, 52% chose the answer that was marked correct, that the force holding the metal atoms in the crystal was the attraction between the positive metal ions and the 'free' electron pool formed from the valence electrons donated by each atom. Both of these percentages were considered low for questions that were thought to be relatively simple.

The metal structure is very complex and therefore difficult to explain, as discussed in the introduction. The 'positive ion - electron sea' model helps to explain how the electrons move so easily when a current is passed through the metal. However the model creates problems when considering the forces actually holding the ions in place as such a loose-sounding structure is hard to justify with the strength of metals. In fact in a group of forty chemistry teachers who were shown the questionnaire results, there were three or four who were not happy with the answers accepted as correct. In their case, they preferred the spheres as atoms rather than ions and considered that the metallic bond was the attraction between metal atoms and their loosely-held valence electrons. This alternative model, also found in Wooff and others (1990) is much more useful for explaining the strength of metals, but is not so suitable for explaining electrical conduction. As Teacher Y said

> 'Basically if you relate the structure to the conductivity of the metal, you have to talk about the 'free' electrons of 'the sea of electrons' and (to do that) you're got to talk of ions....one of the students showed me that and I said I thought the model (in the text) was a bit loose...'

All the teachers interviewed were happier with the 'sea of electrons' model but readily appreciated its shortcomings. When the writer explained the confusion that a number of the interviewed students had about what the electrons do and where they come from, (several thought the spheres were metal atoms and the electrons came from outside), Teacher X1 said:

> 'Yeh, but the confusion comes not in terms of what metals are like but the explanation of their properties in terms of the model...its the electron sea model that is the difficult model, you can't even model it very well....I have a random selection of close-packing polystyrene balls and I mentally pour golden syrup all over them sticking them together, but in reality you can't do that'.

It is easy to appreciate the difficulties of the students when teachers cannot only not agree on the answers, but have major problems presenting the material !

(c) <u>Molecular Bonding</u> The problems the students had with this section occurred in the last question about the gas particles released on vapourisation. Only 17% were able to identify the gas particles released as molecular PCl_3. In other words, only the intermolecular bonds break when a substance goes from the liquid phase into the gas phase; the intramolecular bonds remain intact. The teachers were not surprised.

Teacher Z:

> 'That's an old, old one...I still have people most years telling me that when you boil water you get hydrogen and oxygen'.

But teacher X1 pointed out:

> 'Mind you, they could argue that because it was an unknown compound they're not sure what comes off....because often when they vapourise something it decomposes.'

Teacher W2 made the same point:

> 'PCl_5 can decompose to PCl_3 and chlorine comes off - they might have remembered that from equilibrium because its an example that is used and got it mixed up'

But teacher W1 wondered if the students had been influenced by the 'State of Matter' model in Form 3.

> 'They could get the idea that when the particles all fly apart when the substance goes from a liquid to a gas...you know how they act that our...they may think that all bonds completely break, and never reconsider it later.'

Of interviewed students eight mentioned seeing chlorine in the compound and therefore thinking that chlorine gas would be produced. There was no evidence that they had any other basis for their answer.

(d) Ionic Bonding Here the chief misconception of the students was the 'ionic molecule'. As mentioned when discussing molecules earlier, they have commonly been defined by science teachers in junior classes as the smallest units of a compound. This definition makes the compound - molecule relationship analogous to that of the element - atom, the atom being the smallest unit of the element. This is a simple model for students and would rarely prove a problem until Form 6 chemistry. Here, however, it gives rise to major difficulties as the large group of salts are ionically-bonded networks, and molecules have nothing to do with their formation.

As Teacher Y said:

> 'I find so many students saying NaCl is a molecule. I talk with the Form 3 and Form 4 students of particles so we don't get this word molecule sloping out...Try to talk of empirical formula and molecular formula at

Form 6 and kids think when you've got NaCl you've just got one molecule'.

Teacher W2 suggested that the misconception wasn't only due to a simple, if incorrect definition; there could be some logical reasoning behind it.

'I'll tell you where this pairing up forms confusion...when you have a precipitate form we also talk of the ions pairing up, ...and those hydroxides don't appear to form crystals ....they're so minute'..

However, teacher Z feels that this misconception can be avoided by the use of models.

'We've got the usual models of ionic and covalent compounds and even if I don't go into great detail about it at least they can see that there's no such thing as a molecule of NaCl....

The idea of five of the interviewed students that there was an 'historical' molecule of NaCl did not surprise the teachers. This issue will be treated in the discussion.

(e) Bonding and its Electrical Nature Teacher W2 noted the need to keep talking about electrical forces

'Bonding is always the attraction of the positive nucleus for the negative electrons of the other atom...its always to do with electrons..more or fewer..you have to keep stressing it because they don't get that far in their thinking..'

Another teacher, W1, pointed out that electrostatics is not really given much prominence in the curriculum. It is likely to be covered by rubbing a plastic ruler against a piece of wool and then using the charged ruler to pick up bits of paper in Form 4 and may not get much further development. Taber (1994) noted the need to keep stressing electrostatic forces when dealing with bonding; in his opinion this would help students to come to terms with the ideas of an extended lattice.

(2) Student Frustration/ Teacher Frustration

All the interviewed teachers agreed that their students found the structure and bonding topic very difficult. The description of 'a solid, straight-forward slog' (Teacher Z) seemed to sum it up well. When the interviewer mentioned that the students were frustrated by their lack of understanding, there was no surprise.

Teacher X1

> 'and the terms.....when I ask about properties they keep talking about bonding...the terminology..the difference between properties and bonding...there's so little experimental work you can do and so much new language..its an indigestible bunch of stuff'

and teacher X2

> 'I really work fairly hard at this...trying to help them get a handle on bonding..trying to drag it together'

Teachers felt there had to be good deal of teacher input into this area, and lots of discussion about terms.

Teacher W1

> 'There also needs to be a lot of discussion about the terms they have already heard of....they can have such funny ideas about them. But that's not easy, they can <u>really</u> turn off if you begin doing something they fell they already know'

The teachers are aware students have to confront their own understanding and it was generally felt that not many of them readily get around to doing this.

(3) <u>Timing Of Topic</u>

Generally this topic is taught near the beginning of the year. This is not simply because most text books place the material in the early chapters, but teachers see it as a central topic and therefore feel it should be introduced early. So it was interesting that three of the six classes in this survey had a different approach to timing. Two classes from school X did not cover the topic until the last term, and school Z introduced the particular aspect in term 1 and left the crystalline structures until the third term.

Teacher X1:

> 'Why do we do it later ? Well, its relatively hard and they don't really need it earlier. You can do precipitation, and equilibrium...and the quantitative mole stuff and then titrations...you don't need bonding for any of that...and then acid-base and that's the first time..the weak acid-base stuff and there's a bit of bonding there so we talk about the molecular stuff...you just pull out bits when you need it...you don't even need it for oxidation-reduction ...Its a quite complex and there isn't much practical work'...

Teacher X2:

> 'And we leave it until the kids feel positive towards chemistry and they're less likely to give up on it...they still find it hard, no matter when you do it'.

The other approach was to divide the topic.

Teacher Z:

> 'We start with some quantitative chemistry and then go into atomic structure..we really start at the beginning again, whether they've done it
>
> or not...all the parts of the atom and atomic mass calculations, and then straight into a very simple treatment of ionic and covalent bonding and Lewis diagrams and stop right there...go into something interesting like oxidation-reduction...We try to keep their interest up...that atomic structure is fairly boring and not one you can easily adapt to experimental work..We come back to it about the start of term 3 (to the crystalline structures) and only spend two weeks on it ..there's not much you can do to perk it up'

This issue will be revisited in the final chapter in conjunction with other suggestions for the presentation of the topic.

CHAPTER III

DISCUSSION

The overriding impression from the research is of the number and variety of misconceptions that exist among the students. Not one of the 110 papers was free of some misunderstanding, and there was no area of the questionnaire that did not reveal a number of misconceptions.

The three aims of this research as presented in the introduction were:

* What are some of the misconceptions Form 6 chemistry students have with the basic concepts of atomic structure and bonding ?
* Why have these misconceptions arisen ?
* How might teachers introduce and develop this topic with their students so as to prevent these misconceptions from forming ?

The misconceptions that were uncovered have already been detailed in the results. Here the two procedures used to uncover those misconceptions will be evaluated. The usefulness of the teacher interviews will be considered and this will be followed by an analysis of the class results. A discussion of the possible causes of the misconceptions will conclude this section.

1. THE RESEARCH PROCEDURE

(1) <u>The Questionnaire</u>

The first procedure, the questionnaire, was used as a survey to detect possible misconceptions. There could be some debate about whether the use of a questionnaire was the best method of initially determining misconceptions. Undoubtedly the interviews with the students uncovered far more detail about misconceptions, reinforcing the strong support Osborne and Gilbert (1980) gave to this methodology for identifying students' understanding and misconceptions in science. However it is very difficult for a teacher at one school (as the writer was) to manage to visit another school for interviews during a school day. For this reason, the questionnaire was the only practical tool available for initial screening.

The content, format and the timing of the questionnaire itself could have been improved. It could be argued that the questionnaire was too ambitious. Rather than a general coverage of the topic, it might have been advisable to check only those areas that have been shown in the literature to cause concern. However, since a literature search of the topic did not reveal that confusion about the nature of the metallic bond had been found before, this vindicates the decision to run with the overall coverage.

The diagrams used for molecular bonding and covalent bonding may have been over-simplified as they did not present the three-dimensional nature of the networks. However it was considered that the complexity of three-dimensional diagrams could add further confusion. There is no evidence that the two-dimensional diagrams misled the students.

The questionnaire was five pages in length. Twenty minutes was allowed for each class to complete the paper. This appears to have been a bit too short for some of the students, according to those interviewed, as less than half the students explained their thinking in the section on Bonding in General.

(2) The Student Interviews

The second procedure, the student interviews, was used to provide details of the areas of confusion uncovered by the questionnaires. Much more accurate information was obtained by this method and in a few cases, awareness and self-correction of a misconception occurred. The interviews did not follow a set sequence as each of the students had a unique assortment of problems. However the five topics chosen from the questionnaire were introduced at both interviews with each of the students. It is important to evaluate the interviews with respect to their design, timing and the questioning skills of the interviewer.

The design of the interviews involved the use of cards and models. The cards, used to discuss the interrelationships between atoms, ions, molecules, elements and compounds helped to focus the student on the topic of the questioning. Concept mapping, a technique developed by Novak and Gowin (1984) and used most successfully for science students by White and Gunstone

(1992) would have been ideal for this situation, but it was found that none of the teachers had previously used concept maps with their students, and the necessary introduction would have required more time than was available.

The simple materials used to build the metallic and ionic crystal models had the merit of being new to the student, although again there was the disadvantage that they were only two-dimensional. Three-dimensional models would have been more accurate and one of the earlier ideas was to use Molymod, a very common set of plastic rods and balls used with all of these classes. However the Molymod idea was discarded as it is time-consuming to use for the construction of larger three-dimensional models. It was considered that the simpler models would be just as effective when focusing on the nature of the bonds. The simple model used for questioning what happens when a molecular substance is vapourised was also deemed adequate for the purposes of discussion.

The organisation of the research called for two interviews, the first one at least two weeks after the completion of the topic. The purpose of the two-week delay was to reduce as far as possible any advantage that might be gained by recall, even though the questionnaire did supply almost all the facts needed. In fact one of the students did mention that she 'knew' the difference between atoms and ions for the test but had forgotten it. There are some basic facts that one would hope those in Form 6 chemistry would not be able to forget two weeks later !

The second interviews were held at the end of the year after the final examinations. They were held to determine if the students had realised their misconceptions during the year, and what had triggered this realisation. If considered only with respect to their initial purpose, the second interviews were less than successful. However they proved useful for two quite different reasons. Firstly, they showed the durability of the original misconceptions. Nearly all of the students retained their misconceptions intact, and in one case, when a girl actually recognised her misconception about the vapourisation of NH_3 at the first interview, she retained it at the second. The other advantage was that the students were more relaxed as the format and the interviewer were familiar, and it was possible to go into greater detail about their understanding. However, in general there was little indication that the students had even become aware of their original misconceptions during the year, although in two instances students mentioned that they had sorted out an original misconception while reviewing for the final exam.

Another aspect that could have been improved was the questioning skill of the interviewer. Students in these interviews were concerned to get the right answer. The result was that when they didn't feel they could explain what they thought, or they started to get confused, there was silence, and the interview was in danger of grinding to a dead end. In these cases the interviewer, after repeating the original statement of the student to no effect, had to provide some steering to keep the interview going, and the concern is that this may have disguised some of the misconceptions.

(3) <u>The Teacher Interviews</u>

The teacher interviews weree used to canvass the opinions of the teachers about the major misconceptions found on the questionnaires. They were carried out after the questionnaire results had been collated but before the student interviews had taken place. The interviews might have been more successful if the interviewer had gone through the questionnaire in detail and asked the teachers to explain the performance of their classes on each question. But it can be readily imagined how successful that approach would have been; and these were busy colleagues doing the interviewer a favour by supplying their time and cooperation in using their classes. So what was the value of the teacher interviews ?

Each of the five topics discussed with the students was also discussed with the teachers. In many cases, the teachers were able to point out how the misconceptions could have developed. They also revealed the difficulties of teaching such conceptual material to students who had little experience in dealing with concepts. The problems that carried through from the prior learning of the students in junior science and Form 5 were highlighted, particularly in the areas of understanding of the term molecule, and of the bonding in metals. These problems while not necessarily unique, are a consequence of the New Zealand curriculum structure in science, and are unlikely to change, even when the new curricula are fully introduced. The motivation of many students was also mentioned. Chemistry is a subject needed for many career choices, and many students therefore take it without being particularly interested in it. It is in the difficult conceptual areas such as atomic structure and bonding that teachers are faced with many students decidedly lacking a 'thirst for chemical knowledge' (Johnstone,1993). And the problems with language were as much a teacher concern as a student concern. An 'indigestible bunch of stuff' is a worthy title for this topic both from the point of view of the students who are trying to learn it and from that of the teacher who is trying to promote their learning.

2. ANALYSIS OF THE CLASS RESULTS

The results of the 110 questionnaires were pooled to get the percentage results presented on the first of the tables and the figures in each section. It would have been more accurate to use a larger pool of students; but the difficulties of interviewing at schools further away from the writer's own school made this impractical. The inclusion of the questions from the questionnaire in the presentation of the tables was done to make them easier to follow. The results of the questionnaires have been presented and were used in choosing the students to interview. Possible causes of the misconceptions uncovered will be treated in the next section.

The second tables in each section compared the results of the six classes. In spite of the distortion caused by percentages of classes no bigger than 21 students, it is important to discuss the significance of the larger differences between the classes noted in the summary under each of the result tables.

In the first of the tables, Table 2, less than 50% of the students in two of the classes W1 and Z appeared aware that the number of protons determines the identity of the atom. In the next question, most of the class Y students who had very good results for the other four questions did not seem to realise that the number of protons in the nucleus equals the number of electrons outside the nucleus. It seems very likely that the teachers concerned have taken for granted that the students had covered these points in Form 5 where they are part of the syllabus.

In table 4, less than 50% of the students in all the classes answered the question on the type of ions formed by elements correctly. At this level, most elements in their experience would form only one type of ion, except for iron which forms a 2+ and a 3+ ion, and copper which forms a 1+ and a 2+ ion. However both of these ions are positive. Possible reasons for the errors of classes X1 and X2 have already been covered, but the equally poor performances of the other classes are not explained. Have the teachers here failed to point out that in general metals only form positive ions and non-metals negative ions, or has this point been implied when working out the formation of ions from elements when going across a row of the periodic table and students have failed to recognise it ?

In Table 6, classes W1, W2, and Z had significantly greater trouble with the questions on the formation of the oxide ion, and only half of classes W1 and W2 recognised that the oxide ion had a 2^- charge. It is difficult to accept that any chemistry teacher would have failed to cover this point, so did the students in these classes fail to learn their ion tables, or did they cram them too quickly and then forget them ? Or are they a poorer cohort than the rest ?

The size and shape of molecules is material new to Form 6. In new material lack of understanding is more likely to result from an omission by the teacher and it certainly looks as if the teacher in class W1 had failed to adequately cover the two reasons for the shape of a molecule. Generally classes W1 and W2 appear weaker than the others, but class X2 is less aware that unshared electron pairs lie closer to the central atom than shared electron pairs than class X1.

In the table on Metallic Bonding, Table 10, only class X1 had satisfactory scores, and class X2 had the worst of the lot. Class Z had only two students who correctly answered the first question about the nature of the spheres. Metallic bonding is generally covered in Form 5, but is part of the section on the bonding of the four different types of crystals in the Form 6 syllabus. Did the teachers concerned consider that as it was covered in Form 5 the students already knew it, or is this misconception due to some other factor ? The results strongly suggest that these teachers had failed to check on their student's understanding of the nature of metallic bonding; however, other possible causes for the misconceptions in this area will be discussed later.

Table 12 indicates the performances on the questions about Molecular Bonding. Here class W2 and Z had problems with the nature of the intermolecular bonds, and classes W1, W2 and X1 had problems with the nature of the intramolecular bonds. The other questions were very evenly answered, possibly because this is also an area which is first introduced in Form 6. The majority of students in all the classes failed to recognise the nature of the particles released on vapourisation and this point will be discussed when dealing with the possible causes of the misconceptions.

Table 15 gives the results of the two questions on Covalent Bonding and the two on Ionic Bonding. Discounting question F1 where so many students answered carbon instead of atom or carbon atom, classes W1 and Y show significantly better understanding of Ionic Bonding than the others, and classes X1 and X2 has a greatest number of students who thought that ionic bonds could exist between two metals or two non-metals.

The table below, Table 16, is presented as a general summary of the class performances. The class performance on each question of the questionnaire was examined and the question number was entered on the table if the majority of students had given an incorrect response. Only three questions, B4, Evii and F1 were not included as in these cases all classes had less than 50% of the students responding correctly. All other questions have been used.

TABLE 16

Questions in which the majority of Students of Each Class Gave the Incorrect Answer

Ques/ Sect	Class W1	Class W2	Class X1	Class X2	Class Y	Class Z
Table 2	A3					A3
Sect.A					A4	A4
Table 6	B5(b)	B5(b)				B5(b)
Sect.B		B5(c)				
Table 8	C1					
Sect.C		C6	C6	C6	C6	C6
Table 10	D1			D1	D1	D1
Sect.D	D2	D2		D2		D2
Table 12	E(iii)	E(iii)			E(i)	
Sect.E						
Table 15				G1(a)		
Sect.F/G		G1(b)		G1(b)		G1(b)
	G2	G2	G2	G2		G2
TOTALS:	8(5)	8(7)	2(2)	6(4)	3(1)	10(6)

The three questions omitted from the table were:

* B4 whether atoms of elements can form positive ions in one reaction and negative ions in another
* Evii the particles released on vapourisation of the molecular PCl_3
* F1 the identity of the particle in the giant covalent network of diamond, where so many answered carbon instead of atom or carbon atom.

The third 'error' has already been discussed, and the other two will be dealt with in the section on possible causes of misconceptions.

The totals at the end are a general measure of class performance. The bracketed numbers represent the totals when only the material new to Form 6, that is Shape and Size of Molecules, Molecular Bonding, Covalent Network Bonding and Ionic Bonding, is considered. It can be seen that classes X1 and Y performed notably better than the rest. The possible reasons for these results need to be considered:

* **the competence of the teachers**. All of the teachers concerned were experienced teachers and very concerned to be doing their best for their students, even to taking part in this research. Teacher competence is a very difficult issue and there is insufficient material here to make any judgements.
* **the failure of the teacher to check the understanding of prior learning.** This is more likely to be the reason of the results for the sections on Atoms, Ions and Metallic Bonding. The point needs to be made that checking factual knowledge, which is the usually accepted meaning of the term prior learning, is not enough. For these areas it is the conceptual understanding that needs to be checked and corrected. For class X1, either the teacher did this very well, or their previous learning was very good.
* **the omission of some new material by the teacher**. This could account for the errors of class W1 on the question of the reasons for molecular polarity (C.1) and of classes W2, X2 and Z on the types of ions needed for the formation of ionic bonds.
* **the ability of the class as measured by tests and exams**. There was no screening done to compare the ability of the students nor the level of entry required by the school for admission to Form 6 chemistry. School Certificate results might have been compared, but for five of the six

classes these were obtained by Internal Assessment, and are only relatively comparable between schools because of the individual school differences in the structure of the Internally Assessed Science courses. Class Y was the top class of two and the other was not surveyed, which also adds to the problems of comparison as none of the other schools banded their classes.

* **the conceptual ability of the class**. Science up to and including Form 5 has very little conceptual material, and some students who have previously done well by factual recall have real problems in Form 6 chemistry with conceptual material. In any case comprehension of concepts does not necessarily tie in with test results, as Phillips and Phillips found (1991). They reported that in several studies in the States the performance of students who could do well on the problem-solving questions of most traditional tests did not correlate at all well with their results on conceptual questions.
* **the timing of the topic in the school year**. School X did the topic at the end of the year, and School Z divided the topic, doing atomic structure first and bonding later. This question of timing and the reasons for it will be considered later.
* **the type of class**. It should be noted, although there is not enough information for further analysis, that the three top classes were all co-ed. Is it possible that the single-sex classrooms at this level are less serious in their approach to their studies ? less mature ? more likely to take a 'hard' subject even if they are not very able ?

Such an analysis is far from conclusive. There are obviously many factors that can be used to explain class performance and these are only some of them. The possible failure of the teachers to check understanding and the timing of the topic will be discussed in the recommendations.

3. POSSIBLE CAUSES OF THE MISCONCEPTIONS

The results of the questionnaire determined the five topics used for consultation in the interviews. Here the misconceptions uncovered in each of the topics will be discussed with reference to their possible cause.

(1) Elements and Compounds versus, Atoms, Ions and Molecules

This is the area of most of the major misconceptions found in this research. Some of the confusion could be attributed to a lack of knowledge of basic facts. Form 6 students, for example, should be expected to know that protons are found in the nucleus, the number of protons of an atom does not change in a chemical reaction, the number of protons determines the identity of the atom, and ions are formed when atoms gain or loose electrons. They will have been introduced to the terms element and compound well down the school, in Form 4 or even before without a problem. The definitions usually accepted are

An element is a pure substance made up of one kind of atom only.

A compound is a pure substance made up of two or more different kinds of atoms.

These two definitions obviously require the introduction of the term atom as the smallest particle of a substance. The term ion is usually introduced at Form 4 with varying success. Ions are generally defined as atoms or groups of atoms that have gained or lost electrons. Thus by the beginning of Form 6 students, especially those interested enough to wish to go further with chemistry, should have a fair understanding of those four terms. But it is a different story for the term molecule. Three specific misconceptions found in this area concerned the meaning of the term molecule -

* **Molecules are particles of elements only**
* **All elements are made up of molecules**
* **Ions combine to form molecules**

and there was the frequent implication that all compounds were made up of molecules. As the teacher X2 pointed out, the difficulty with the term lies in the fact that some, but not all, non-metal elements are molecular; most covalently-bonded compounds, but not all, are molecular, but ionic compounds hardly ever (and for their level never) form molecules. In attempts to simplify the concept some Form 4 and Form 5 science teachers teach that molecules are the simplest particles of compounds. And just as Mitchell and Gunstone (1984) reported in their study of students introduced to chemistry with this definition, it leads to nothing but confusion. As they said students are unable to go much further without soon meeting the exceptions to that definition, and it is in this topic in Form 6 chemistry where it is contradicted head on.

The questionnaire section on the formation of ions revealed that many students are unaware of the general rules regarding the formation of metal and non-metal ions or have confused them with oxidation numbers (Question B.4). The misconception, that elements can form positive or negative ions depending on the reaction, has already been discussed. Although there is no concrete evidence that oxidation numbers contributed to the confusion, it remains the most likely explanation and the difference between ion formation and oxidation numbers needs to be carefully stressed by teachers.

The other common cause of confusion was the lack of precision in the use of language. As Johnstone found (1993) and the teachers interviewed in this study readily acknowledged, many students have difficulties in distinguishing between the macroscopic terms of element and compound, and the sub-microscopic terms of atom, ion and molecule. Again teachers, as Selley (1978) pointed out, may be partly to blame. This time it is not so likely to be the junior science teachers as the Form 6 chemistry teachers themselves. As Johnstone says, we slide easily around the 'triangle of terminology' and many of our students may not be quick enough to follow us. In fact, this problem may be more widespread than these results indicate as it was not specifically investigated on the questionnaire.

(2) Metallic Bonding

Of all the misconceptions found, this might have been expected to be the easiest to explain. It is very difficult for even graduate chemists to adequately explain the nature of a metallic bond. However, this reason should not be accepted too readily. In spite of the fact that some New Zealand chemistry teachers, mentioned earlier, did not agree with the 'positive metal ion - electron pool' model, all the teachers of the classes in this research had used this description with their students. These misconceptions therefore could be due to the inconsistency of that model with a widely-used text that was issued to students of schools X, Y and Z, (Wooff and others, 1987) but it does not explain the poor showing of school W, especially class W1. It would appear that the model itself is more difficult for students than teachers realise.

Perhaps the idea of teacher X1 of having a three-dimensional network and pouring golden syrup all over it is not so absurd !

(3) Molecular Bonding

An agreeable result was the finding that a good majority of the students had little trouble with the distinction between intermolecular and intramolecular bonding, in spite of the findings of Peterson and others (1986) that many Australian students confused the intermolecular bond with the covalent bond. The lack of ability of students to distinguish between the two has also caused the examiners of the New Zealand Bursary examination to complain in the recent past (N.Z.Q.A. Chemistry Marking Schedule and Examination Commentary, 1993; N.Z.Q.A Chemistry Marking Schedule and Examination Commentary, 1994). Presumably the teachers in this research have covered this point well right from its introduction. But it would appear that student understanding is limited to the theoretical, as so few were able to identify the molecules in the gaseous state, and here the findings are identical to those of Treagust (1986). The confusion might be due to the way the 'Change of State' topic is introduced in junior science. The change from solids to liquids to gases has been generally introduced in Form 3 in a topic called the 'Particle Nature of Matter'. It is then illustrated by modelling a close-packed network of solid particles loosing their structure in the liquid state and separating completely in the gaseous state. A student might carry on with the idea that a complete break-up of a substance into their smallest particles occurs when the substance becomes a gas, and then translate that later into atoms, as the particles at that level are not distinguished as atoms or molecules.

(4) Ionic Bonding

After reading the findings of Taber (1994) of student 'molecular framework' theories of the ionic bond, the results here were not unexpected. While only one student explicitly called the ionic 'unit' a molecule, eleven of the twenty interviewed students did believe that the negative ion transferred its electron to a specific positive ion before both of them then entered the ionic lattice, a sort of mass wedding idea. As the students were then able to acknowledge that the specific partnership broke down, and the ions in place were equally attracted to all the ions around them in the lattice, the misconception would not cause many problems at this level; as Steve, one of the interviewed students said, 'it works, I suppose'.

There are at least two science teaching topics that would encourage the formation of this misconception. The first would be ion formation in Form 5 where the teaching of the topic is usually identical to that outlined by Ben-Zvi and others (1987). As they stated, most teachers would explain, for example, how the sodium atom loses an electron to become a positive ion, and how a chlorine atom gains an extra electron to become a chloride ion. At least some would indicate that there was a direct transfer, and few would mention anything about an ionic lattice. Even if not stated this could easily convince students that the electron was passed directly from the sodium atom to the chlorine atom, and that the two were then bonded because of their opposite charges.

The second topic is related; here the student learns how to prepare the formula of an ionic compound. In a sample explanation, the correct formula for Magnesium chloride would require the Mg^{2+} ion to be balanced by two Cl^- ions thus implying, if not specifically pointing out, that the three atoms then form a electrically neutral group. This would be done in all schools in Form 5 science as part of the chemistry section. It is little wonder that the more able students who can correctly write ionic formula think of them as groups or even molecules, and have a hard time shaking the idea when it still 'works' in Form 6.

(5) <u>The Electrical Nature of Bonding</u>

As mentioned in the results, it appears that few students had ever thought of the electrical nature of bonding. The electrical nature of the covalent bond that eluded the students in the two quoted interviews; they could readily define the covalent bond as a shared electron pair but had never thought about how the pair acted as a bond. Electrostatics is a topic introduced at Form 4; and as mentioned earlier may not get much attention. Students without a clear idea about electrostatic forces will be unable to make much sense of bonding.

(6) <u>Other Misconceptions</u>

The questionnaire revealed more misconceptions than have been treated in detail in the student and teacher interviews. There was confusion with the identity of the intermolecular, intramolecular and ionic solids, and problems with the polarity of small molecules. However there was a limit to what could be discussed in a short student interview and so the more basic misconceptions were used.

This discussion has reviewed the research methods used and considered the significance of the performances of the six classes. Possible causes of the misconceptions, the second aim of the research, have been discussed. The final chapter will contain some suggestions for teachers that might be used to prevent these misconceptions from forming.

CHAPTER 1V

CONCLUSIONS AND SUMMARY

MAKING SENSE OF ATOMIC STRUCTURE AND BONDING

1. IMPLICATIONS OF THE RESEARCH

The last aim of this research was to identify presentation styles, teaching strategies or other factors that might be used to prevent these misconceptions from forming. The results and the discussion of their possible causes indicate that at least five points should be considered:

* revisiting the terms and the concepts
* taking care in the 'triangle'
* using concrete models
* discarding the atomic introduction
* getting students to use the language

(1) Revisiting the Terms and the Concepts

The terms referred to here are those of atom, ion, molecule, element and compound. All of these terms are introduced in or before Form 5 in the new curriculum (Science in the New Zealand Curriculum, 1993) and there is the problem of what definitions have been used and what the students have learned. There is likely to be a lot of variation in both knowledge and understanding in our Form 6 classes, even if the students have been at the same school. And it is probable that there will be some misconceptions, especially with the term molecule. So the first step is to identify what the students already know; that is, to review the ideas and definitions they have. The second step is to persuade them away from the idea that they already all know about atoms and ions and the relationships between these terms and molecules, elements and compounds and try to make them receptive to new, more correct definitions. As Taber (1995) suggests 'it is in the nature of chemistry that the appropriate meaning for a term develop as the student passes from school to college to university'. And there are teaching strategies that would be ideal for this topic. Concept maps were suggested for use with science concepts by White (1988) and are already widely used in junior science, (Brodie,1992; Adamczyk,1994; Sizmur,1994) They would be ideal here to determine the inter-relationships between the terms, and could be coupled with peer discussion to make the students aware of their own misconceptions, and to help them to develop more accurate meanings. Also without such a careful review on the part of the Form 6 chemistry teacher, corollaries to atomic structure such as the fact that the atom is identified by the number of protons, and the fact that metals only form positive ions while non-metals only form negative ions may never be actually presented to the student.

The second suggestion is to review any of the concepts that may have been introduced earlier. Apart from the definition of a molecule, the nature of the metallic bond, and the electrostatic nature of all bonding also presented problems for the students. In both cases, checking the students' ideas about these concepts and discussing the correct view is important.

(2) Taking Care in the 'Triangle'

Chemistry teachers are already well aware of the need to be precise and specific about terms they use. This heading is a suggestion that teachers become more aware of their propensity of 'sliding around' Johnstone's triangle (1993). It is the language use that Selley (1978) noted, the mixing of the macroscopic and the submicroscopic terms that comes so easily to teachers but leaves our students way behind. At times, it cannot be avoided, but then it should be brought to the students' attention, and the reactions can be dealt with at both levels separately. For example, the comment that Selley used, 'Hydrogen ions are reduced to hydrogen gas' is better in two parts, 'Hydrogen gas is produced which indicates that hydrogen ions are being reduced to molecular hydrogen'.

(3) Using Models

During the interviews three students became aware of their misconception about the covalent bonds of a molecule breaking on vapourisation. In each case, it was the use of the model of the solid substance with the obvious difference of the bonds between the molecules and those within the molecules that triggered understanding. Solomon (1995) feels that teachers should be more ready to supply working models for their pupils, 'to help them deal with the less tangible theoretical ideas which hand-waving by the teacher so often fails to bring to life'. A suitable 'working' model for bonding is not easy to picture, but a construction model might do, however simple. The use of tangible models cannot be undervalued, even if their use is restricted to demonstration.

The misconceptions of the students concerning metallic and ionic bonds may also be overcome with the use of models. Some older ionic models may still be about in schools, but they can be made more easily now that polystyrene balls are widely available. The use of an ionic model and the emphasis on the electrostatic nature of bonding should help students who, like the 35% in this survey, have the idea that ionic bonds can form between two metals as well as between two non-metals. As teacher Y, whose class scored well in this section on ionic bonding pointed out, the use of older models that have been in schools for some time helped to overcome the misconception that the ions form a 'pair' before entering the ionic network. As mentioned, the metal model of 'positive ions in an electron sea' is not easy and should be carefully discussed, especially as it also may have been introduced in Form 5 or even before.

One further suggestion is to revisit earlier models the students have been given. An example here is the usual model presented for the changing of state. As mentioned students may have the impression that all particles completely disintegrate from the particle model they were given in junior science. A careful review of the model and discussion that its particles actually represent molecules and not atoms is needed.

(4) Discarding the Atomic Introduction

There is no doubt that the concepts of atomic structure and bonding are basic to our understanding of chemistry, but do we need to introduce our subject through them ? Chemistry teachers would agree with Cannizzaro when he said it was impossible to eliminate atomic theory in the course of his teaching, but why is it given the prominence it currently receives so early in our teaching programme ? One reason is that most current chemistry teachers are themselves the product of the conceptual approach of the '60s and '70s that did introduce chemistry through these concepts. Also both of the most frequently used texts for

Form 6 in New Zealand place Atomic Structure in the first few chapters (Wooff and others,1987; Sayes,1986). Is there a good case for leaving the topic until later in the year, or for introducing it slowly as needed ?

The two classes of school X (class X1 had the top scores in the questionnaire, and class X2 was placed third) studied the atomic structure and bonding topic at the end of the year. Their teachers admitted there were some aspects that needed to be introduced occasionally, and they did so as needed. As teacher X2 put it, 'We wait until the students feel positive about chemistry', and there is little evidence that the introduction of atomic structure and bonding early in Form 6 does much for class enthusiasm. Another approach was that taken by teacher Z, where atomic structure was covered near the beginning of the year, but the bonding aspect was left until the end of the year. This reduced the amount of concentrated 'slog', and was done to keep the enthusiasm of the class as high as possible. The argument that atomic structure and bonding is so central that it has to be covered early so that everything can be related back to it needs to be thought through; it could equally well be introduced later and related back to everything else. An alternative approach could be to focus on the practical aspects of chemistry, especially where it can be related to their everyday experiences, and retain enthusiasm while slowly introducing the concepts as they are needed. This is not to adopt the position of Fensham (1994) who argues that for an introductory study of chemistry 'the phenomena of everyday and applied chemistry have little or no need for atomic scale explanations'. But it does echo the opinion of Johnstone (1993) who suggests a slower approach in introducing the macroscopic concepts of element and compound, the submicroscopic concepts of atom, ion and molecule, and the representation of all of this by symbols, formula and equations. He feels that 'students, trying to process too much, overload, causing frustration and bewilderment'. This sounds very much like the problem of Lucy and Christine; the frustration with all the terms. The answer to the 'indigestible bunch of stuff' may well be to digest it a little at a time !

(5) <u>Getting Students to Use the Language</u>

Can anything be done to help students with the language of chemistry ? The plea from the students in the interviews, the introductory quote from Byrne and others (1994) are not new problems; teachers themselves faced them as students and many feel they are the main reason so many students drop out of chemistry. But the language is a vital part of the science and the challenge is to make it comprehensible. Like any language it must be used, not just by the teacher, but by the students to question and to discuss their ideas. As Herron (1984) noted 'The major influence that research into psychology and education has had on my teaching is the portion of time I spend telling students what I think versus the portion I spend asking them what they think'. Watts and Alsop (1995) stress the need for students to ask questions to gain conceptual understanding. With so much to present that is new and foreign, chemistry teachers can be tempted to 'chalk and talk' too much and the students fail to practice the language for themselves. The communication of chemists may not be a lyrical language but it 'is integral to an understanding of chemistry and should be revised at each level' (Chemistry in the New Zealand Curriculum, 1994).

2. SUMMARY

This research has uncovered some of the misconceptions that Form 6 chemistry students have with the basic concepts of atomic structure and bonding. Some of the misconceptions are far more prevalent than others. The main areas of confusion found among the students concern the concept of a molecule, the bonding of metals, the type of particle found when a molecular substance is vapourised and the way ionic bonds form. Confusion with the language that is required for these concepts is common.

The Christchurch teachers interviewed were aware that the topic of Atomic Structure and Bonding presented many problems for their students. However this is the first time a systematic study of the misconceptions in this area of the Form 6 New Zealand chemistry syllabus has been carried out to my knowledge. Interviews with the students backed by discussion with the teachers indicated the likely causes of the misconceptions.

It is hoped that the teaching strategies suggested on consideration of the results and their causes will help to prevent the misconceptions from forming or correct the ones which have already formed. Both the teachers and the students should be challenged by these proposals; the students to question their own understanding and the teachers to carefully guide their students to do so. Unless that happens, the result for many students is that atomic structure and bonding will never really make sense.

ACKNOWLEDGEMENTS

I would like to express my appreciation to Professor Graham Nuthall for his kind assistance, encouragement and advice with this research project; to Dr. Peter Harland for his advice with planning the questionnaire and reviewing the final document, and to Messrs Norman Baird and Peter Metcalfe for their valuable assistance at proof-reading it.

I am very indebted to the teachers who so graciously helped me by arranging for their classes to take the questionnaire and for agreeing to be interviewed, and to all the twenty students who thought it was all a bit peculiar but were unfailingly polite and helpful.

Finally, I would like to thank my colleagues at Villa Maria College for their cheerful encouragement and my two sons at home, Peter and John, who did such a good job of keeping the show on the road.

Christchurch, February 1996

REFERENCES:

ADAMCZYK, P. and others (1994) Concept mapping: a multi-level and multi-purpose tool. School Science Review 76 (275): 116-124

ANDERSEN, H.O. Readings in Science Education for the Secondary School. Indiana University: The McMillan Company, 1969

AUSUBEL,D. Some Psychological and Educational Limitations of Learning by Discovery. In Andersen, H.O. Readings in Science Education for the Secondary School. Indiana University: The McMillan Company, 1969. p.97-114

BENT, H.A. (1984) Uses (and Abuses) of models in teaching chemistry. Journal of Chemical Education 61: 774-777

BEN-ZVI, R. and others (1987) Students' Visualisation of a chemical reaction, Education in Chemistry 24: 117-120

BEN-ZVI, R. and others (1988) Theories, Principles and Laws. Education in Chemistry 25: 89-92

BODNER, G.M. (1992) Why Changing the Curriculum May Not Be Enough. Journal of Chemical Education 69: 186-190

BRODIE, T. (1991) Concept Mapping. School Science Review 73: 120-123

BUTLER, P and LONGBOTTOM, J. (1994) New school science curriculum leaves some aims ambiguous. The Press, Christchurch.14 July

BYRNE. M., JOHNSTONE, A.H., and POPE, A. (1994) Reasoning in Science: A Language Problem Revealed ? School Science Review 75: 103-107.

CAMPBELL, J.A. (1962) Chemistry - an Experimental Science ; the CHEM Study Course. The School Review 70: 51-62

CARR, M. Book Review of 'Challenging NZ Science Education' by Michael Matthews for Access. In Bell, B. Responses to "Challenging NZ Science Education" by Michael Matthews. University of Waikato, Hamilton, N.Z., 1995. p.11

CHEMICAL EDUCATION MATERIAL STUDY. Chemistry - An Experimental Science. 1st edition. W.H.Freeman and Company , San Francisco and London, 1963. 466p.

CHRISTIANSEN, G.S. and GARRETT, P.H. Structure and Change : An Introduction to the Science of Matter, W.H.Freeman & Company, San Francisco, 1960. 608p.

CLARK, M. and VERE-JONES, D. Science Education in New Zealand: Present Facts and Future Problems. The Royal Society of New Zealand Miscellaneous Series 15, 1987. 39p.

CROS, D. (1986) Conception of first year university students of the constituents of matter and of notions of acids and bases. European Journal of Science Education 8: 305-314

CROUCHER, M. and PACKER, J. A Chemistry Guidebook, Heinemann, 1983. 363p.

de VOS, W. and others. (1987) A New Road to Reactions, Part 4. The Substance and its molecules. Journal of Chemical Education 64: 692-694

DRIVER, R. and others. Children's Ideas in Science, Open University Press, 1985. 208p.

ELVINS, C. and others. Chemistry in Context : Chemistry One. Heinemann Educational Australia, 1990. 364p.

FENSHAM, P.J. Beginning to Teach Chemistry. In Fensham P.J. and others The Content of Science : A Constructivist Approach to Its Teaching and Learning. The Falmer Press, London, 1994. p.14-28

GABEL, D.L. (1987) Understanding the Particulate Nature of Matter. Journal of Chemical Education 64: 695-697

GAGNE, R.M. A Psychologist's Counsel on Curriculum Design. In Andersen, H.O. Readings in Science Education for the Secondary School. Indiana University: The McMillan Company, 1969. p.331-339

GARFORTH, F. (1982) The future of secondary level chemistry. Chemistry in Britain: 108-112.

GRIFFITHS, A.K. and PRESTON, K.R. Paper presented at the National Association for Research in Science Teaching, San Francisco, 1989

HAIGH, M. Making Sense of "Making Sense". In Bell, B. Responses to "Challenging NZ Science Education"by Michael Matthews. University of Waikato, Hamilton, N.Z., 1995.

HARLAND, P.W. (1991) The 7th-Form Chemistry Syllabus.Time for a Change? Chem NZ 45: 3-12

HAWKINS, D. Part II. Constructivism : Some History. In Fensham, P.J. and others The Content of Science : A Constructivist Approach to Its Teaching and Learning. The Falmer Press, London, 1994. p.9-13

HERRON, J.D. (1984) Using Research in Chemical Education to Improve my Teaching. Journal of Chemical Education 61: 851-854

INTERNATIONAL GENERAL CERTIFICATE OF SECONDARY EDUCATION : Chemistry Syllabus 1989, University of Cambridge Local Examinations Syndicate

JOHNSTONE, A.H. (1993) The Development of Chemistry Teaching : A Changing Response to Changing Demand. Journal of Chemical Education 70: 701-705

LAVERTY, D.T. and McGARVEY, J.E.B. (1991) A 'Constructivist' Approach to Learning. Education in Chemistry 28: 99-102

MALLISON, G.C. (1975) A Summary of Science Education. Research in Science Education

MERRILL, R.J. Chemistry: An Experimental Science. In Andersen, H.O. Readings in Science Education for the Secondary School. Indiana University: The McMillan Company, 1969. p.411-417

METCALFE, H.C. and others. Modern Chemistry. Holt, Rinehart and Winston Limited, New York, 1970. p.73

MINISTRY OF EDUCATION. Chemistry in the New Zealand Curriculum. Learning Media, Wellington, 1994. 39p.

MINISTRY OF EDUCATION. Science in the New Zealand Curriculum. Learning Media, Wellington, 1993. 135p.

MITCHELL, I.J. and GUNSTONE, R.F. (1984) Some Students Conceptions Brought to the Study of Stoichiometry. Research in Science Education 14: 77-88

NAKHLEH, M.B. (1992) Why Some Students Don't Learn Chemistry : Chemical Misconceptions. Journal of Chemical Education 69: 191-196

NEW ZEALAND QUALIFICATIONS AUTHORITY. Chemistry Marking Schedule and Examination Commentary. University Entrance and Bursaries Examination, 1993. p.1

NEW ZEALAND QUALIFICATIONS AUTHORITY. Chemistry Marking Schedule and Examination Commentary. University Entrance and Bursaries Examination, 1994. p.1

NOVAK, J.D. (1984) Application of Advances on Learning Theory and Philosophy of Science to the Improvement of Chemistry Teaching. Journal of Chemical Education 61: 607-612

NOVAK, J.D. and GOWIN, D.B. Learning How To Learn. Cambridge University Press, Cambridge, 1984.

NUFFIELD CHEMISTRY. Longman Group Limited, London, 1966.

OSBORNE, R.J. and GILBERT, J.K. (1980) A method for investigating concept understanding in science. European Journal of Science Education 2: 311-321

PETERSON, R. and others. (1986) Identification of Secondary Students' Misconceptions of Covalent Bonding and Structure Concepts Using a Diagnostic Instrument. Research in Science Education 16: 40-48

PHILLIPS, C.A. and PHILLIPS, P.S. (1991) Concept learning versus problem solving among chemistry students: a comparison between the UK and the USA. School Science Review 73: 110-113

POPPER, K. Principles of the Scientific Method. Unpublished manuscript held in Central Library of the University of Canterbury

REVISED NUFFIELD CHEMISTRY : Teacher's guide I. Longman Group Limited, London, 1975. 267p.

REVISED NUFFIELD CHEMISTRY : Chemists in the World. Longman Group Limited, London, 1979. 93p.

ROWE. M.B. (1983) Getting Chemistry off the Killer Course List. Journal of Chemical Education 60: 954-956

SATCHELL, D.P.N. Beginning O-level chemistry. Chemistry in Britain 18: 161-167

SAYES, E.M. Form 6 Chemistry Revision, ESA Publications, Auckland, 1986. 265p.

SCHOLLUM, B. (1992) Highlighting the Learner in Chemistry. NZ Science Teacher 69: 35-41

SELLEY, N.J. (1978) The Confusion of Molecular Particles with Substances. Education in Chemistry 15: 144-145

SIZMUR, S. (1994) Concept mapping, language and learning in the classroom. School Science Review 76 (274): 120-125

TABER, K.S. (1994) Misunderstanding the ionic bond. Education in Chemistry 31: 100-102

TABER, K.S. (1995) Time to be Definitive ? Education in Chemistry 32: 56

TREAGUST, D. (1986) Evaluating Students' Misconceptions by Means of Diagnostic Multiple Choice Items. Research in Science Education 16: 199-207

WATTS, M. and ALSOP, S. (1995) Questioning and conceptual understanding: the quality of pupils' questions in science. School Science Review 76 (277): 91-95

WESTMEYER, P. The Chemical Bond Approach to Introductory Chemistry. In Andersen, H.O. Readings in Science Education for the Secondary School. Indiana University: The McMillan Company, 1969. p.406-411

WHITE, R.T. Theory into Practice I. In Fensham, P.J. Developments and Dilemmas in Science Education. The Falmer Press, London, 1988. p.121-132

WHITE, R.T. and GUNSTONE, R.F. Probing Understanding. The Falmer Press, London, 1992.

WOOFF, A.H. and others. Chemistry for Sixth Forms, Longman Paul, Auckland, 1991. p.112 and p.170.

APPENDIX 1:

NAME: ____________________

QUESTIONNAIRE ON ATOMIC STRUCTURE AND BONDING:

You are invited to take part in this research project by completing the following questionnaire. It is not a test. The aim of the project is to investigate the understanding that you and other students have of these concepts. The questionnaire is anonymous, and you will not be identified as an informant without your consent. If you wish, your paper will be returned to you with the correct answers. Thank you for answering this questionnaire as accurately as you can.

A. ATOMS:

The definition of ***an atom as the basic unit of chemical composition*** has many implications. Please tick one box for each of the following statements.

	True in all cases	True in some cases	Never true
1. The protons of an atom are found in the nucleus	☐	☐	☐
2. The number of neutrons of an atom equals the number of protons	☐	☐	☐
3. The number of protons determines the identity of the atom	☐	☐	☐
4. The number of protons in the nucleus of an atom equals the number of electrons outside the nucleus.	☐	☐	☐
5. Only the electrons take part in chemical reactions	☐	☐	☐

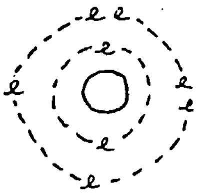
B. IONS:

Ions are atoms that have become charged.

Please tick a box for the following statements.

1. When an ion forms from an atom the number of protons may change	☐	☐	☐
2. When an ion forms from an atom the number of electrons may change	☐	☐	☐
3. Only the outermost energy level (shell) is affected by gain or loss of electrons in a chemical reaction	☐	☐	☐
4. In some reactions atoms of an element will form negative ions but in other reactions the same atoms will form positive ions	☐	☐	☐

The following diagram is of an oxygen atom.
Next to it please draw a similar diagram of the oxygen (oxide) ion.



Answer the following in the space provided.

a) How many protons does the oxygen atom have ? _____

b) How many protons does the oxide ion have ? _____

c) What is the charge on the ion ? _____

The following terms can be used to fill in the blanks in the statements below. You may use the same term as many times as you wish.

IONS **MOLECULES** **ATOMS**

COMPOUNDS **ELEMENTS**

a) __________ gain or lose electrons to form __________

b) __________ can combine chemically to form __________

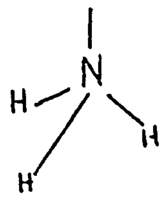
and __________ can combine chemically to form __________

c) __________ are the simplest units of all __________

d) __________ are the simplest units of some __________

e) A compound cannot be made up of both __________ and __________

THE SHAPE AND SIZE OF MOLECULES:



molecule of ammonia has a trigonal pyrimidal shape as this diagram. (Each line represents an electron pair).

Identify from the choices below the reason for this shape (Circle your choice)

a) the unshared electron pair
b) the shared electron pairs between the N and each H
c) both (a) and (b)

What is the type of bond between the N and each H ? (Circle one choice)

a) polar covalent b) ionic
c) non-polar covalent d) Van der Waals

3. NH_3 is a polar molecule (one that has a dipole). Indicate on the diagram above which end would have the positive charge.

4. This is a Lewis diagram of NH_3. Is there any difference in the behaviour of the electrons marked with an **o** and those marked with an **x** ? _______

5. Do all the electron pairs lie at the same distance from the central Nitrogen atom ? If not, explain.

____

____

6. Approximately how many molecules are there in an average drop of water ? (Circle your choice)

   a) Less than 200

   b) Between 200 and 1000

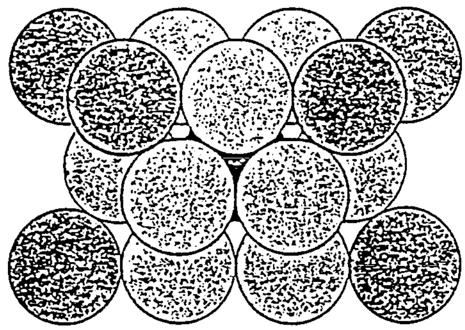
   c) Between 10^6 and 10^{12}

   d) Between 10^{12} and 10^{20}

   e) More than 10^{20}

<u>D. METALLIC BONDING:</u>

Most metals are already crystalline solids at room temperature. This is a diagram of the metal structure.



Please circle your choice for the following questions.

1. If this metal were magnesium, do the individual spheres represent

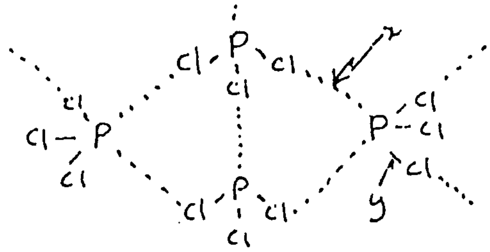
   a) Magnesium atoms
   b) Magnesium 2^+ ions
   c) Magnesium nuclei with no electrons

2. How would you explain the force holding the metal atoms in this crystal ?

   The attraction between
   a) metal atoms and their loosely-held electrons
   b) positive metal ions and their loosely-held electrons
   c) positive metal ions and the 'free' electron pool formed from the valence electrons donated by each atom
   d) positive metal nuclei and the free electron pool formed from all the electrons donated by each atom

E: MOLECULAR BONDING:

When the temperature is reduced, PCl_3, (a liquid at room temperature) forms a crystalline solid shown in the diagram below.



Please circle your choice for the following questions. or answer in the space provided.

i) In this model are the bonds marked x

a) polar covalent
b) ionic
c) non-polar covalent
d) Van der Waals

ii) Are these same bonds

a) intermolecular - between the molecules
b) intramolecular - within the molecules

iii) Are the bonds marked y

a) polar covalent
b) ionic
c) non-polar covalent
d) Van der Waals

iv) Are these same bonds

a) intermolecular - between the molecules
b) intramolecular - within the molecules

v) Which bonds are the strongest, x or y ? ________

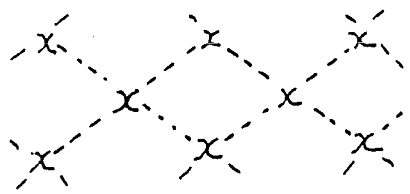
vi) When the substance melts, which bonds break first, x or y ? ________

vii) When PCl_3 vaporizes, what particle(s) are released as gas particles ?

____

F: COVALENT NETWORKS:

A few substances have a giant covalent network structure. The best-known example is diamond. The following diagram shows the network structure of diamond.



Using the diagram, answer the following questions in the spaces provided or circle the letter of your choice

1. What type of particle does the x represent ? __________

What kind of bond is there between the x's ?

a) polar covalent　　b) ionic
c) non-polar covalent　　d) Van der Waals

IONIC BONDING:

positely charged ions are needed to form ionic bonds.

swer yes or no in the provided space.

Can ionic bonds occur between

a) two metals ______
b) two non-metals ______
c) a metal and a non-metal ______

In the space provided draw an ionic network diagram similar to those given for the other types of crystalline solids. Use the following three terms to label it.

Positive ion　　Negative ion　　Electrostatic bond

BONDING IN GENERAL:

Please indicate whether you agree or disagree with the following statements and give a brief reason.

1. All bonding is electrical in nature.

____

____

2. Van der Waals bonds are much weaker than covalent bonds.

____

____

3. All compounds that contain a metal are composed of ions.

____

____

4. All compounds that do not contain a metal are composed of molecules.

____

____

APPENDIX 2:

To be supplied to students chosen following the initial questionnaire:

UNIVERSITY OF CANTERBURY: DEPARTMENT OF EDUCATION

PROJECT INFORMATION

You are invited to participate as a subject in a research project on your understanding of atomic structure and bonding. The aim of this project is to investigate your comprehension and those of other students of these concepts.

You will be asked to take part in an interview to discuss your answers to the questionnaire and to answer some other questions about the topic. This will take between 15 and 20 minutes. In term three there will be a follow-up questionnaire and a similar interview. The interviews will be carried out at lunch time or immediately after school, and there is no foreseeable risk involved.

The results of the project may be published, but you may be assured that your name will not be used, your school will not be identifiable, and that your part in this project will not be made public without your consent. To ensure anonymity and confidentiality, all tapes and the written questionnaires will be destroyed at the end of the study.

This project is being carried out under the direction of Professor Graham Nuthall, who can be contacted at 3667-001. He will be pleased to discuss any concerns you may have about participation in the project.

This project has been reviewed and approved by the University of Canterbury Human Ethics Committee.

You are welcome to keep this information sheet, but if you agree to take part, would you please complete the consent form below for my records.

Yours sincerely

Loanne Metcalfe

....

CONSENT FORM:

I have read and understood the description of the above-named project. On this basis I agree to participate as a subject in the project, and I consent to publication of the results of the project with the understanding that anonymity will be preserved. I understand also that I may at any time withdraw form the project, including the withdrawal of any information I have provided.

Signed .... Date....................